Integrating fuzzy analytic hierarchy process into a multi-objective optimisation model for planning sustainable oil palm value chains

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Abstract

This study presents a novel integrated decision model for optimal planning oil palm value chains (OPVC) incorporating decisions to minimise biodiversity losses by limiting the expansion of oil palm plantations as needed and generate value from its waste products. The model can answer the following types of question:

> What is the best way to deploy OPVC in terms of both economic and environmental factors wherein objectives are integrated systematically by experts? How can the demands for palm oil and palm-based materials and energy products be satisfied with and without considering additional land for plantation? Which conversion technologies will be needed, when and where should these be deployed? How can the resources be managed subject to utilisation, production, import, export and transportation constraints?

The planning model developed involves two components: (1) a decision framework using fuzzy analytic hierarchy process (FAHP) to incorporate experts' knowledge in planning and design under uncertainty and (2) a mixed integer linear program (MILP) to determine the optimal expert-based OPVC design. The framework was applied to different scenarios for the Malaysian palm oil industry. Results show that the demand for crude palm oil (CPO) in Malaysia can be fully satisfied while the international demand can be satisfied by about 60% in 2050. However, in order to minimise environmental impacts and risks of biodiversity losses, the contribution of Malaysia towards satisfying global demand for palm oil should be kept to a minimum. Moreover, the current plantations can satisfy future CPO demand after 5 to 10 years, after which best practices to improve palm oil yield and alternatives comparable to palm oil will be needed. The framework can potentially contribute to the development of better policies in the future through the proposed systematic approach in dealing with sustainability issues in the palm oil industry.

Keywords: Oil palm value chain; optimisation; environment-food-energy-water nexus; fuzzy analytic hierarchy process; decision analysis.

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Nomenclature

Abbreviations

BTS	Biomass Tri-generation System
CPO	Crude Palm Oil
EFB	Empty Fruit Bunch
EFEW	Environment-Food-Energy-Water Nexus
FAHP	Fuzzy Analytic Hierarchy Process
FFB	Fresh Fruit Bunch
FPP	Fuzzy Preference Programming
MCDA	Multi-Criteria Decision Analysis
MILP	Mixed Integer Linear Program
OPVC	Oil Palm Value Chain
PBB	Palm-based Biorefinery
PKS	Palm Kernel Shell
POME	Palm Oil Mill Effluent
PSE	Process Systems Engineering
TFN	Triangular Fuzzy Number

Indices

$b \in \mathbb{B} \subset \mathbb{R}$	index for raw material resource
$c \in \mathbb{C}$	index for conversion technologies
$i \in \mathbb{I} \subset \mathbb{Q}$	index for impacts ($i \,\epsilon$ {Economic, Climate Change, Water, Biodiversity})
$k \in \mathbb{K} \subset \mathbb{Q}$	index for criteria
$p,\, p' \in \mathbb{P}$	index for planning period
$q,\, q' \in \mathbb{Q}$	index for alternative or criteria used for pairwise comparison
$r \in \mathbb{R}$	index for resources
$s \in \mathbb{S}$	index for month types or season
$t \in \mathbb{T}$	index for transport infrastructures
$y \in \mathbb{Y}$	index for year types
$z,\, z' \in \mathbb{Z}$	index for zones

Parameters

$\mathrm{A}_{b}^{\mathrm{gmax}}$	Maximum area of plantation for resource b that can be used in the value chain throughout the planning horizon (ha)
$\mathrm{A}_{b,z,p}^{\mathrm{lmax}}$	Maximum area of plantation for resource b that can used for zone z at planning period p (ha)
$\mathrm{AD}_{t,z,z'}$	Actual logistic distance between zone z and z' through infrastructure t (km)
$\mathrm{AE}_{b,z}$	Plantation area of existing plantation of resource b (i.e. oil palm) in zone z (ha)
$\mathrm{b}_{t,z,z'}$	Binary parameter that determines whether infrastructure t exists between zones z and z'

$\mathrm{Conv}_{c,p,r}$	Conversion factor of technology c in producing (+) or consuming (-) resource r in planning period p (tons/ton, tons/MWh, MWh/ton or MWh/MWh)
$\mathrm{D}^{\mathrm{PROD}}_{c,i,p}$	Discounting factor for capital impact for technology c invested in planning period p
$\mathrm{D}^{\mathrm{OM}}_{i,p}$	Discounting factor for operating impacts for planning period p
$\mathrm{DDIT}_{t,r,i,p}$	Distance-dependent transportation impact parameter for transporting resource r using infrastructure t in planning period p
$\mathrm{D}_{r,z,s,y,p}$	Demand of resource r in zone z in month s in year y in planning period p. (tons/mo or MWh/mo)
$\mathrm{D}^{\min}_{r}$	Minimum fraction of demand set for resource r to be satisfied.
$\mathrm{E}^{\min}_{r,y,p}$	Fraction of export duty set for minimum export duty of resource r in year y in planning period p
EP_r	Export price of resource r (MYR/tons or MYR/MWh)
$\Delta\mathrm{T}$	Uniform lengths of planning periods (y)
f	Discount rate
$\mathrm{FIT}_{t,r,i,p}$	Distance-independent transportation impact parameter for transporting resource r using infrastructure t in planning period p (MYR/ton or tons CO_2/ton or MYR/MWh or tons CO_2/MWh)
$\mathrm{FIPP}_{c,i,p}$	Fixed production impact of production technology c in planning period p (MYR/unit)
$\mathrm{ILP}_{i,z,p}$	Impact parameter for expanding oil palm plantation in zone z in planning period p (No of species at risk/ha)
$\mathrm{IIP}_{r,i,p}$	Impact parameter for import of resource r in planning period p (MYR/ton or tons CO_2/ton)
$\mathrm{IPP}^{\mathrm{CAP}}_{c,i,p}$	Capital impact parameter for investing in technology c in planning period p (MYR/unit)
$\mathrm{IUP}_{r,i,s,y,p}$	Impact parameter for utilisation of resource r in month s in year type y in planning period p (MYR/ton or tons CO_2/ton or m^3/ton)
j	Finance rate
$\mathrm{l}_{q,q'}$	Lower bound of triangular fuzzy number used to evaluate alternative or criterion q against alternative or criterion q'
$\mathrm{m}_{q,q'}$	Modal value of triangular fuzzy number used to evaluate alternative or criterion q against alternative or criterion q'
n^{sy}_{s}	Number of successive repetitions of month s in year y (mo/y)
n^{yp}_{y}	Number of successive repetitions of year y in planning period p (y)
NF_i	Normalisation factor for impact i
$\mathrm{NE}_{c,z}$	Number of existing conversion units of technology c in zone z
$\mathrm{NER}_{c,z,p}$	Number of existing conversion units of technology c in zone z that retires in planning period p
Price_r	Selling price of resource r (MYR/ton or MYR/MWh)
$\mathrm{Prod}^{\min}_{c}$	Minimum production rate of technology c (tons/mo or MWh/mo)
$\mathrm{Prod}^{\max}_{c}$	Maximum production rate of technology c (tons/mo or MWh/mo)
$\mathrm{RE}^{\mathrm{duty}}_{r,y,p}$	Export duty of resource r in year y in planning period p (tons/y)
$\mathrm{RE}^{\min}_{r,y,p}$	Minimum rate of export of resource r in year y in planning period p (tons/y)
$\mathrm{RE}^{\max}_{r,y,p}$	Maximum rate of export of resource r in year y in planning period p (tons/y)

$\mathrm{RF}_{c,p,p'}$	Binary parameter that determines whether a conversion units of technology c invested in planning period p' retires in planning period p
$\mathrm{RU}^{\max}_{r,z,s,y,p}$	Maximum rate of utilisation of resource r in zone z in month s in year y in planning period p. (tons/mo)
$\mathrm{RI}^{\max}_{r,z,s,y,p}$	Maximum rate of import of resource r in month s in year y in planning period p. (tons/mo)
ς	Scaling factor to convert units (e.g. MYR, tons CO_2, etc.) to million units (e.g million MYR, million tons CO_2).
T_c	Operating life of technology c (y)
$\mathrm{T}^{\max}_{t,r}$	Maximum capacity of transport infrastructure t for transporting resource r (tons/mo)
$\mathrm{u}_{q,q'}$	Upper bound of triangular fuzzy number used to evaluate alternative or criterion q against alternative or criterion q'
$\mathrm{VIPP}_{c,i,p}$	Variable production impact of production technology c in planning period p
w_i	Weight for impact i in the objective function obtained from the result of FAHP
$\mathrm{Y}_{b,z,s,y}$	Base yield of resource b (i.e. oil palm FFB) in zone z in month type s and year type y. (tons/ha/mo)
$\mathrm{YF}_{p,p'}$	Yield factor of plantations in planning period p invested at planning period p'
YFE_p	Yield factor of existing plantation in planning period p relative to the base yield in a typical yearly cycle.

Variables

$a_{q,q'}$	Crisp score of alternative or criterion q in comparison with alternative or criterion q'
$AI_{b,z,p}$	Additional plantation area invested of resource b (i.e. oil palm) in zone z (ha)
c_k	Priority weights of criterion k obtained solving the FPP model of the pairwise comparison matrix between the set of criteria $\mathbb{K}$
$FIP^{\mathrm{OM}}_{i,p}$	Total fixed operating impact resulting from resource production in planning period p (million MYR)
$IE_{i,p}$	Total impact resulting from export of resources in planning period p (million MYR)
$II_{i,p}$	Total impact resulting from import of resources in planning period p (million MYR)
$IL_{i,p}$	Total impact resulting from expanding the oil palm plantation area in planning period p (No of species at risk)
$IP^{\mathrm{Cap}}_{i,p}$	Total capital impact resulting from investing new conversion units in planning period p (million MYR)
$IT_{i,p}$	Total impact resulting from resource transportation in planning period p (million MYR or million tons CO_2)
$IU_{i,p}$	Total impact resulting from resource utilisation in planning period p (million MYR or million tons CO_2 or million m^3 H_2O)
λ	Overall degree of satisfaction or consistency of pairwise comparison of alternatives or criteria
$N_{c,z,p}$	Number of conversion units of technology c in zone z in planning period p
$NI_{c,z,p}$	Number of conversion units of technology c invested in zone z in planning period p

$NR_{c,z,p}$	Number of conversion units of technology c in zone z that retires in planning period p
$Prod_{c,z,s,y,p}$	Production rate of technology c in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
$R_{i,p}$	Total revenue generated from selling products in planning period p (i = Economic, million MYR)
$RE_{r,z,s,y,p}$	Rate of export of resource r in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
$RI_{r,z,s,y,p}$	Rate of import of resource r in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
$RP_{r,z,s,y,p}$	Rate of production of resource r in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
$RT_{r,z,s,y,p}$	Rate of transportation of resource r in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
$RU_{r,z,s,y,p}$	Rate of utilisation of resource r in zone z in month s in year y in planning period p (tons/mo or MWh/mo)
s_{ik}	Priority weights of impact i derived from solving the FPP model of the pairwise comparison matrix between the set of impacts $\mathbb{I}$ based on criterion k
$TR_{t,r,z,z',s,y,p}$	Rate of transportation of resource r from zone z' to zone z through infrastructure t in month s in year y in planning period p (tons/mo or MWh/mo)
$VIP^{\mathrm{OM}}_{i,p}$	Total variable operating impact resulting from resource production in planning period p (million MYR or million tons CO_2 or million m^3 H_2O)
w_q	Priority weight of alternative or criterion q
$w_{q'}$	Priority weight of alternative or criterion q'

Highlights

- Expert-based optimisation (MILP) planning model for oil palm value chains
- Incorporates expert value judgment in planning and design under uncertainty
- Maximises economic benefits while minimising negative environmental impacts & risk of biodiversity loss
- Systematic approach for dealing with sustainability issues in oil palm value chains
- Application to different scenarios for the Malaysian palm oil industry

1. Introduction

1.1. Background

Palm oil is regarded as the world's main source of vegetable oil due to its excellent yield, low land requirement and long life time [1]. The average yield of palm oil (in ton/ha/yr) is ten times greater than that of soybean, five times greater than that of rapeseed and eight times greater than that of sunflower [2]. Palm oil is useful as cooking oil, as confectionery and cosmetic additives and as a raw material for biodiesel. Its raw material, the oil palm fresh fruit bunch (FFB), has a life cycle of 30 years in which the maximum yield is generated in more than two-thirds of its lifetime. To meet the current and future demands for vegetable oil for food and energy applications, palm oil shows a significant advantage over its alternatives as these would require more land to produce the same yield as oil palm. However, several issues arise with palm oil plantations such as the negative impacts of land use change, biodiversity losses and waste generation. The conversion of peatlands and forests into palm oil plantations contribute respectively to increased greenhouse gas emissions and biodiversity losses [3]. Tree losses due to plantation expansion have led to the decrease in the number of orang-utan species in South East Asia, particularly in Malaysia and Indonesia [4]. On the other hand, peatland conversion results in positive carbon emissions due to the release of stocked carbon resulting from the land use change [5]. Lastly, a typical palm oil mill (POM) produces four tons of waste by-products for every ton of palm oil produced [6]. These by-products include empty fruit bunches (EFB), palm kernel shell (PKS), palm mesocarp fibre (PMF) and palm oil mill effluent (POME). When left untreated, these will eventually be discarded and will contribute to solid waste generation and water pollution. The Malaysian palm oil industry contributes to 90% of the total biomass supply and has a huge potential for bioenergy applications [7]. In order to produce sustainable palm oil, the issues regarding the palm oil industry need to be addressed through systematic planning and design of future palm oil systems. This work involves the development of a decision model for oil palm value chains (OPVC's) which can be used to manage not only the production of palm oil but also the valorisation of by-products (i.e. POME, PKS, EFB, and PMF).The idea of value chain was first described by Porter & Millar [8] as value-added activities that are "*technologically and economically distinct*". It includes primary activities that involves the physical creation of the products and support activities that provide the infrastructure. A formal definition of value chain was given by Jarvis and Samsatli [9] as "*a network of technologies and infrastructures (such as conversion, transportation, storage) along with its associated activities (such as sourcing raw materials, processing, logistics, inventory management, waste management) required to convert low-value resources to high-value products and energy services, and deliver them to customers*". Creating a value chain framework for oil palm can potentially maximise the benefits and at the same time minimise the negative environmental impacts. Also, a streamlined value chain framework can help address issues in slow development of sustainable palm oil. This could eliminate the need to further expand palm oil plantations, stop conversion of peatlands and forests, and generate valuable products to satisfy demands for energy and materials when incorporated in planning and decision-making. This study develops a novel systematic decision model for optimal planning of OPVC's through process systems engineering (PSE) and multi-criteria decision analysis (MCDA). PSE approaches are established to be useful in addressing relevant planning factors in the development of biomass value chains that are synergistic with the environment-food-energy-water (EFEW) nexus [10, 11] and to sustainable bio-economy in Malaysia [12]. The next subsection discusses previous work on the optimisation and application of MCDA tools for planning palm-based systems.

1.2. Literature Review

Numerous PSE and MCDA approaches have been used for planning palm-based systems including POMs and palm-based biorefineries (PBBs). A review on PSE approaches of palm-based biomass systems has been made by Ng and Ng [13]. Approaches such as supply chain optimisation [14] and life-cycle analysis [15] demonstrate solutions for utilising palm-based biomass to produce valuable products. The following discussion is divided into subsections: plant-scale optimisation approaches, large-scale optimisation approaches, and MCDA tools.

1.2.1. Plant-scale Optimisation

The design of an integrated palm oil biorefinery was developed by Ng and co-workers considering single [16] and multiple [17] ownerships. The methodology involves integrating the processes in a POM to utilise three types of palm-based biomass (i.e. EFB, PKS, and POME) using technologies to produce steam and electricity needed to run the POM. Results from their single-ownership model suggests that excess products such as electricity from biogas can be used to satisfy all of the electricity demands of the biorefinery as well as some external demands. Taking into account multiple ownerships into the design of the integrated biorefinery results in a more representative network configuration by maximising the degrees of satisfaction of each owner [17]. The use of fuzzy optimisation for the multiple-owner model implies that through maximising the satisfaction of each owner results in a higher likelihood of successfully implementing industrial symbiosis and increased economic and environmental performance. Proces synthesis and optimisation considering maximum economic potential, minimum environmental impact, minimum safety impact and minimum occupational health impact were performed by Ng et al. [18]. Andiappan et al. [19] developed a game-theoretic approach for integrating biomass tri-generation systems (BTS), PBB and POM to reduce annual cost.. However, it also suggests that POMs should be made as reliable as possible, since disruptions in POMs can cause a ripple effect on BTS and PBB. Fuzzy optimisation has been applied for PBBs considering both environmental and economic impacts in two problems: upgrading POMs to PBBs [20] and determining the operational flexibility of PBBs subject to uncertainty [21].

These plant-scale optimisation tools considered economic benefits (i.e. maximum profit or minimum costs) in their modelling approach. It is also noted that the goal of each model is either to develop an optimal design or to improve the performance of existing plants. Better plant performance can contribute to additional short-term and long-term economic, environmental and social benefits. These include improved safety impact and occupational health [18] and reduced costs and better environmental performance through coalition [19].

1.2.2. Large-scale PSE Approaches

Optimisation models on large-scale palm oil systems have been developed considering plantation management [22], source-sink matching [23], spatial modelling [24] and EFB valorisation [25]. Abdulrazik et al. [25] developed an extensive linear programming (LP) model for development of pathways to valorise oil palm EFB to energy and chemical products such as ammonia, hydrogen, gasoline, diesel, biocomposites, among others. The model was developed considering steady-state operation with an economic objective (i.e. maximise total profit) subject to process, carbon footprint, biomass availability, demand and transportation constraints. The resulting optimal production levels focused on the production of materials such as biocompost, activated carbon, cellulose, hemicellulose and bioresin and high-value energy products such as biodiesel and biogasoline. A model for planning a closed-loop palm oil supply chain was made by Alfonso-Lizarazo et al. [26] suggesting an increase of 5% in profit for closed-loop supply chain. A simulation-optimisaton framework was developed by Costa et al. [27] for palm-based biodiesel production, taking into account economic, social and environmental aspects into the design. The objective function is to maximise the economic benefits, with the environmental impacts expressed as ecological credits. The study made use of a detailed plant design methodology using AspenPlus to capture the detailed design at the plant level. The study emphasised that transportation and raw material availability are the most important factors in the design. A source-sink matching model was developed by Foo et al. [23] for robust planning of bioenergy supply chains using EFB as the feedstock. The paper emphasised the need to account for uncertainties during planning because scenarios such as anticipated closure or expansion of POMs may arise. The model they developed characterises uncertainties into discrete scenarios with different sets of supply and demands. In the case study presented, cases on two scenarios of EFB supply were considered and the decisions related to the EFB source-sink connections are fixed. The advantage of the model is demonstrated by offering flexible solutions under uncertainty. Mohd Idris et al. [24] developed a spatial optimisation model for oil palm value chains subject to environmental and economic constraints. The paper presents a detailed spatial modelling of Johor state in Malaysia, in which oil palm biomass is converted into electricity. Although the model presents a detailed spatial analysis and environmental impact consideration in different value chain stages, it lacks the consideration of a wide range of products such as transportation fuels. Foong et al. [22] developed an input-output optimisation approach for sustainable palm oil plantations. The model involves determining the best management practices through optimal fertiliser application to maximise the yield of palm oil, in effect, minimising the need for further land expansion. Although the paper contributes by giving recommendations for sustainable palm oil production, the study did not consider the future outlook of the palm oil industry. A framework for risk assessment in palm oil supply chains is developed by Hadiguna and Tjahjono [28], which consists of three steps: risk assessment, performance measurement and supply chain optimisation. The results of the case study, based on the Indonesian palm oil industry, suggest factors such as plantation, production and port storage need to be strengthened to mitigate the risks, especially on the demand side.

Most of these large-scale optimisation tools addressed both economic and environmental factors in the design. The development of these tools allows to gain insights for policy development [24]. Sustainable ways to improve social benefits and acceptance are also considered through risk assessment [28]) and best management practices [22]. Thus, aside from short- and long-term environmental and economic benefits that we can obtain from optimising large-scale palm-based systems, it is important to align the objectives towards policy development and social benefits. Integrating economic and environmental factors was demonstrated through MCDA tools which are discussed in the following subsection.

1.2.3. MCDA Approaches

A few studies are related to the application of MCDA tools in oil palm systems. The synergies and conflicts between key stakeholder's interests are captured using a combined Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis and analytic hierarchy process (AHP) [29]. From their results, the perception of stakeholders to the development of ways to utilise palm-based biomass is greater than the development of first-generation palm biodiesel. The application of SWOT-AHP in capturing stakeholders' interests allows policy-makers to determine a sound strategy for the palm oil industry by taking into account different views of the stakeholders. AHP is also applied to site suitability analysis for oil palm plantation in Thailand to develop a systematic approach of generating weights for each factor in the suitability analysis [30]. The paper discussed a pairwise comparison approach for each site suitability criterion and then populating the pairwise matrix to generate the priority weights for the suitability analysis. Other application of AHP for oil palm systems include selection of best fresh fruit bunch for higher palm oil yield [31] and performance evaluation of palm oil industry [32]. The advantage of AHP in capturing qualitative information can be exploited for integrating different factors including economic and environmental impacts. However, this advantage was not yet applied to multi-objective optimisation of large-scale value chain systems such as for oil palm. Current progress and research gaps are discussed in the next section to highlight the novelty of this work.

1.3. Identified Research Gaps and Novel Contribution

The literature indicates that:

1. Biomass by-products from palm oil production, such as EFB, POME and PKS, are potential sources of valuable products, so utilising them can increase the profitability of OPVCs and at the same time avoid the negative environmental impacts that may result if these are simply discarded.
2. Environmental constraints were considered effectively in oil palm-based systems focusing on the impacts from the production processes and resource transportation.
3. Few papers proposed optimisation-based approaches for the development of best practices for addressing the big issues in palm oil, e.g. loss of biodiversity and climate change impacts due to land conversion.
4. AHP has been demonstrated for a wide range of applications in oil palm systems: from best practices such as FFB selection to incorporating stakeholders' interest into palm-based biomass systems.

These mathematical approaches provide evidences that PSE tools can address issues in planning palm oil systems and MCDA tools can incorporate and integrate stakeholders' perception into the planning of palm oil systems. Few papers developed models specifically for large-scale palm oil systems (i.e. palm oil supply chains, palm-based industrial parks, etc.). These studies involve improving the economic performance is considered more important than the environmental and social performance. At the time of writing, no mathematical tool has been developed that integrates planning through a PSE approach and decision-making through an MCDA approach except for How et al. [33], who proposed a novel method for incorporating sustainability factors for planning palm oil supply chains using both AHP and P-graph methodologies. In addition, expert qualitative judgments are valuable insights to incorporate in planning OPVCs especially when considering multiple conflicting objectives. These objectives can be evaluated based on different criteria such as their importance in generating short- and long-term benefits, developing future policies and producing sustainable palm oil for public consumption, For instance, the growth of demand for palm oil would result to additional economic benefits. However, this can trigger expansion of palm oil plantations, posing risks to biodiversity by deforestation and climate change by peatland drainage. These trade-offs can be addressed through expert value judgment, allowing several impacts to be prioritised based on a systematic decision structure.

The main contribution of this paper is the development of the first systematic and integrated model for optimal expert-based planning of OPVCs with the following novel characteristics: (1) multi-period and spatially-resolved planning to determine investment decisions, (2) accounting of seasonal variations of oil palm yields based on its life cycle, (3) considering multiple high-value product generation from different palm-based biomass sources and (4) incorporation of expert knowledge in the decision-making and planning of the value chains. This paper also fills the research gaps identified above. In this paper, region-wide planning of OPVC incorporates key decisions on the levels of production of palm oil as well as high-value products derived from its biomass considering economic and environmental factors such as economic benefits, climate change impact, water resource impact and biodiversity losses. The OPVC model both incorporates a decision tool and an optimisation model which considers qualitative and quantitative information for future planning of sustainable palm oil industry. This paper also considers uncertainties such as vagueness, ambiguity and imprecision into the decision structure through the application of fuzzy in analytic hierarchy process (FAHP) which, before this study, has never been applied to OPVCs.

The rest of the paper is organised as follows. Section 2 discusses the problem for the planning model while section 3 explains the key elements of the value chain model. Section 4 presents the planning optimisation model and discusses its main components. The results for the Malaysian case studies are analysed in Section 5, in which insights for planning the production of sustainable palm oil are discussed. Lastly, policy insights and concluding remarks are given in Section 6.

2. Problem Statement

The problem that the optimisation model can solve is as follows:

Given:

- Spatio-temporal demands for energy resources (e.g. heat, and electricity), energy vectors and services (e.g. syngas, gasoline, diesel, biogas, jet fuel, etc.) and valuable materials (e.g. fibre mat)
- Spatio-temporal availability of palm-based biomass (i.e. EFB, PKS and POME) in terms of yield and its variation over time, and maximum available land area for plantations
- Characteristics of conversion technologies and transport infrastructures
- Stakeholders' expert qualitative value judgment

Determine:

- Rate of conversion of resources to satisfy product demands in Malaysia and abroad
- Investment in technologies, i.e. number of units and operating capacities, when and where
- Transport infrastructure and rate of transport of resources required between regions
- Overall environmental and economic impacts of the value chain
- Required land area for expansion to satisfy product demand and export

Subject to:

- Satisfaction of product demands and exports

- Conservation laws and physical constraints (i.e. mass and energy balances)
- Production and transportation constraints (i.e. availability, build rate and capacity)
- Palm-based biomass availability
- Land area available for expansion

Objectives:

- Maximise economic performance
- Minimise climate change impact
- Minimise water impact
- Minimise risks of biodiversity losses
- A combination of the above objectives, weighted based on expert's qualitative judgments converted using fuzzy analytic hierarchy process (FAHP)

3. Key Components of Expert-based Oil Palm Value Chains

This section provides the key elements of the expert-based oil palm value chains, namely, time, space, resources, technologies, and experts' value judgment of different objectives. This value chain framework is based on the conceptual framework in the model of Samsatli and Samsatli [34], which has been successfully applied to urban energy systems planning [35], renewable energy value chains [36, 37, 38] and multi-vector energy networks [34, 39]. In this paper, a new mathematical model is specifically developed for oil palm value chains using the conceptual framework from previous studies mentioned and incorporating a systematic method for assigning weights in the multi-objective optimisation model.

For the oil palm value chain optimisation, a planning horizon from 2015 to 2050, illustrated in Figure 1,was chosen to capture the effect of discouraging the expansion of oil palm plantation in the future, since palm oil typically needs to be replanted after 30 years. Recent technological deployments in the region are considered during the first five years of the planning horizon, which subdivided into planning periods with a length of 5 years. Each year is divided into 3 major seasons of similar yield of oil palm FFB as defined in Figure 1, which is adapted from Corley and Tinker [1]. The time representation of the oil palm value chains, captures important decisions at different levels such as investment of technologies for each planning period, demand satisfaction for each planning year and the difference in yields for each season. It also uses non-uniform interval time representation in which similar time elements (i.e. month or year) are grouped into similar types, thus, increasing the computational efficiency. Since investment decisions are made periodically, a planning period of 5 years is selected based on an attractive payback period (3-4 years) for an investment for palm oil technologies to be attractive [17]. This also considers the decision whether plantation expansion is necessary to anticipate possible growth of palm oil demand, however, this decision is made for the next planning period as the yield of palm oil peaks after 5 years. In this study, the model is developed to generate

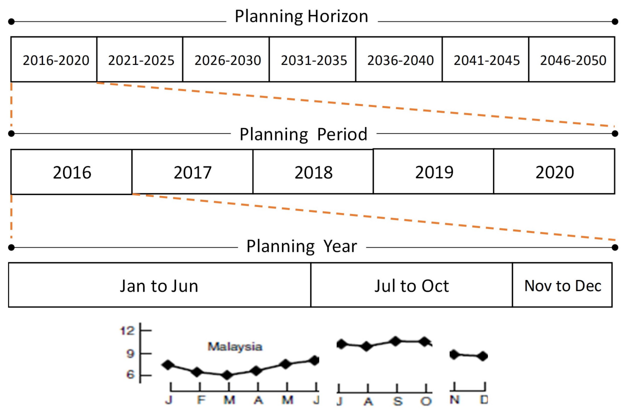


Figure 1: Temporal representation of oil palm value chains and the division of month types based on similarity in yield (based on Corley and Tinker [1])

a preliminary but representative initial design of the value chain subject to the available information about its current status. Any new information or unexpected events (e.g. drought, calamities, etc.) that may happen during the planning horizon can affect the value chain design. The method to adjust the optimal design for new information, specifically for OPVCs, is subject for future work, although the mathematical concept of large-scale systems was demonstrated by a two-step optimal revamp approach [40].

The space element in the oil palm value chain is described as follows. An appropriate scope of the Malaysian administrative boundary is used for the model and it is divided into zones based either on administrative or grid-like divisions. In this study, the resolution considered is based on state division of the Peninsular Malaysia to capture the difference between levels of demand, of energy products and materials, production levels and land availability.

In the value chain model, resources and technologies are interlinked, forming the value web. Resources are classified into raw materials, intermediates, waste products and end-use products. Raw materials are inputs into the value chain, which are usually of low economic value. In oil palm value chains, resources have temporal limitations based on the yield as shown in Figure 1 in which the yield of FFB varies monthly. Conversion technologies interlink the resources and allow the generation of intermediate products and end-use products from raw materials and intermediates. These are considered as the main “value-added activities” in the value chain, adding value to a resource by converting it into another form. It also involves “black-box” conversion, in which the ratio between inputs and outputs are constant. Intermediate resources are produced from conversion processes in the value chain and then converted into higher-valued products to satisfy regional or national demand. End use products such as electricity, heat and transportation fuels are the outputs of the value web and used to satisfy social demand. Waste products are encouraged to be utilised in the value chain to minimise environmental impacts generated by the value chain. This interlinking allows the representation of forward, backward and circular pathways involved in the value chain.

Transportation of resources is represented by transport infrastructures, such as roads or railroads, to deliver materials that can be carried by trucks or trains respectively, electricity transmission lines or pipelines for resources such as biogas or syngas. The zones in the value chain are connected by these transport infrastructures, which have a limited capacity for the transport of materials or energy, e.g. maximum

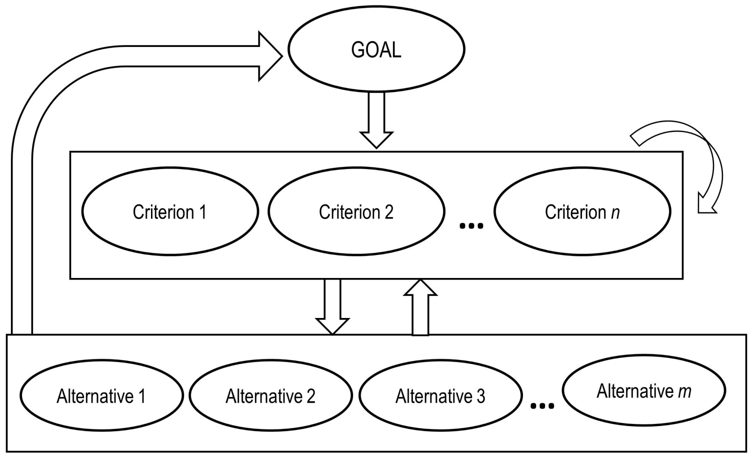


Figure 2: Hypothetical decision structure for incorporating expert value judgment in value chains

flow rate through a pipeline or the maximum power rating of a transmission line. Once invested in, these infrastructures are assumed to be available throughout the remainder of planning horizon after they have been installed.

The value chain model includes an additional component that incorporates expert judgment. This allows the engagement of experts for views during the value chain planning stage especially when prioritising economic and environmental objectives. An MCDA tool such as AHP can be used to incorporate expert stakeholder judgment into the value chain framework. A well-established method of AHP is used in the model due to its organised decision structure and ability to generate insights from a small group of respondents with sufficient expertise [41]. The number of experts required for AHP ranges from a small size of ten to hundreds of participants, although it was demonstrated that AHP can be used for a minimum of ten experts when evaluating key performance indicators for a sustainable palm oil supply chain [42]. The method consists of developing a decision structure composed of several criteria and alternatives with one common goal. An expert is asked to perform pairwise comparisons between elements in the decision structure. For instance, in the decision structure in Figure 2, the arrows from the criteria to the alternatives examine which alternative is more important based on a particular criterion. On the other hand, the arrows that point from the alternatives to the criteria indicate that the criteria can also be evaluated based on the alternatives. The feedback loop in the criteria represents how each of criteria are prioritised against each other. If the alternatives are to be considered in the value chain, the overall weights based on the ultimate goal of the decision structure are to be taken into account. This is represented by the arrow that points from the alternatives to the goal. Lastly, the pairwise comparison matrix is populated to derive the priority weights. The decision structure for OPVCs as well as the procedure to derive the weights for each impact is discussed in Section 4.1. A more advanced form of AHP is used to incorporate uncertainties in expert judgment (i.e. imprecision, vagueness and ambiguity) in the form of fuzzy sets; thus, a fuzzy analytic hierarchy process (FAHP) is integrated into the value web model [43].

These key elements are used to develop the models for the systematic framework of oil palm value chain. In the next section, the framework is discussed along with the associated models at the different steps. Identifying these elements in the value web enables the decision maker to generate scenarios for planning and designing value chains at different levels. An additional key element discussed here allows the decision maker to incorporate his or her choice of weighted objective through a qualitative approach.

4. Integrated Model for Optimal Expert-based Oil Palm Value Chains

The framework for the integrated decision model for optimal planning of OPVCs consists of two major components: the decision tool to determine the priorities between environmental and economic impacts in the value chain and the mixed integer linear programming (MILP) model to generate an expert-based optimal solution for the value chain. Note that the model developed can also be applied to other value chain systems which follows similar decision structure. Figure 3 summarises the decision framework in which the decision model is based on fuzzy analytic hierarchy process (FAHP) and the optimisation model is developed as a weighted multi-objective MILP model. The use of FAHP for the decision model incorporates vagueness of the qualitative response when being expressed as a numerical value. The strength of the FAHP in decision analysis is demonstrated by its capability to account for qualitative expert judgment in which assigning numerical values will give a lot of uncertainty. It also allows to minimise the subjectivity in the judgment in which the consistency of the judgment is maximise through fuzzy preference programming (FPP). When used as a weight for the multi-objective MILP model, qualitative expert judgment can be incorporated in the optimisation. The method enables the conversion of the descriptive responses from the experts into priority weights. These weights are then used in the optimisation model to determine an expert-based optimal solution. The following steps for the tool are summarised as follows:

1. The optimisation model is solved to give the best solution for each objective associated with each impact. The objective function values are used as normalisation factors so that when the objectives are aggregated, the comparisons between them are levelised. The normalising factor for an impact is computed as the ratio of the best economic impact to that of the least value for that impact being minimised. This is used as a numerical factor so that the weights calculated by FAHP will be able to reflect the relative importance between objectives. The economic objective is selected since economic benefits may have a significant trade-off to environmental impacts.
2. The weights for each impact are obtained using the decision structure established for FAHP and represent the relative priorities of each of the impacts. In this case, each impact is evaluated based on numerous criteria and the criteria-based priority weights are solved using the FPP model described in Section 4.1. The optimisation model described has been developed by Promentilla et al. [44] for decision structures involving fuzzy expert judgments. The FPP model demonstrates global optimality in most cases when consistent judgments are made [45]. The model also handles incomplete information as long as the number of judgments made in a pairwise comparison matrix is equal to $Q - 1$, where Q is the number of elements being compared.
3. The weights for each criterion are also solved using the same model in Section 4.1. This generates how important each criterion is when evaluating the impacts.
4. The weights to be used in the palm oil value chain model are solved by the weighted sum of the priority weights of each impact for each criterion.

4.1. Decision Model using Fuzzy Analytic Hierarchy Process

The decision structure for the value chain framework is described in Figure 4. It presents a three-level hierarchical decision structure, having the goal on the first level, the criteria on the second and the impacts

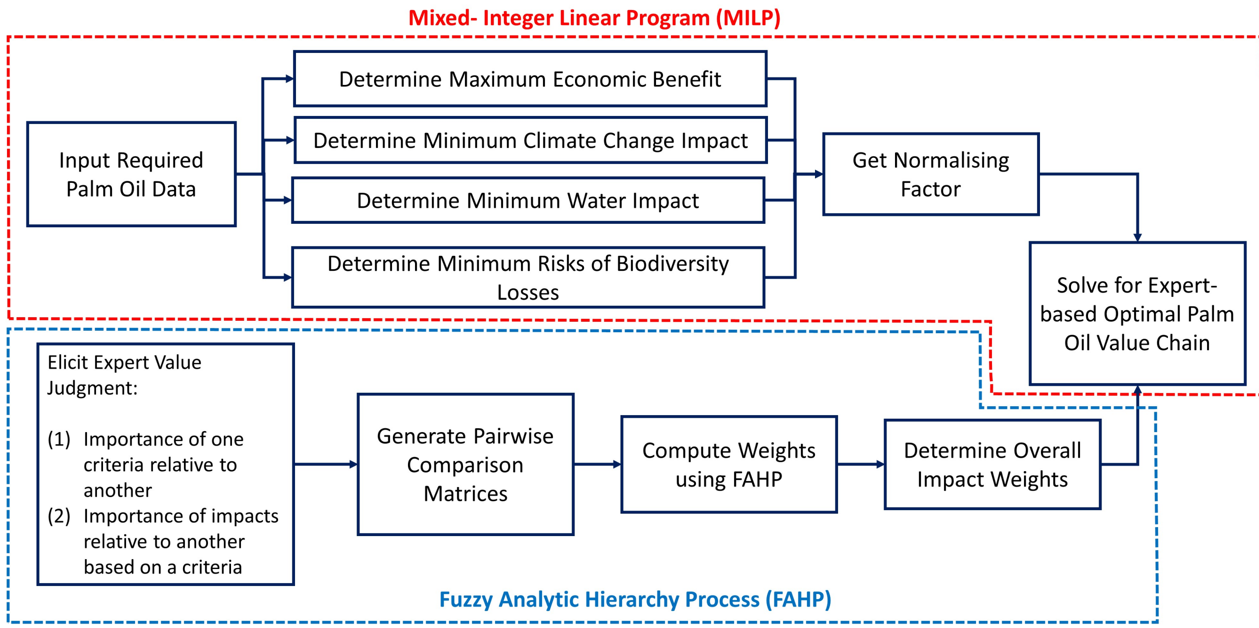


Figure 3: Decision framework for oil palm value chains. Two simultaneous pathways are present (1) determining the normalising factors for each impact and (2) obtaining quantitative expert value judgement using a hierarchical decision structure.

or objectives on the third level. The overall goal (GO) is to determine which impact should be prioritised in the value chain model based on four criteria: short term benefits, long term benefits, policy development and social acceptance. Four impacts are evaluated in this paper: economic benefits, climate change impact, water impact and risk of biodiversity losses. The representation of the required expert judgment is presented as arrows in the decision structure. The arrows pointing from the goal to the criteria represents the priority weights of the criteria with respect to the goal. The arrows pointing from each criteria to the impacts represent the priority weights of each impact with respect to a criteria. The overall weights are then calculated and is represented by the arrows from the impacts to the overall goal. The required value judgments are communicated to experts with substantial background in palm oil industry in Malaysia. Experts' views regarding the important objectives of the value chain are obtained in this way.

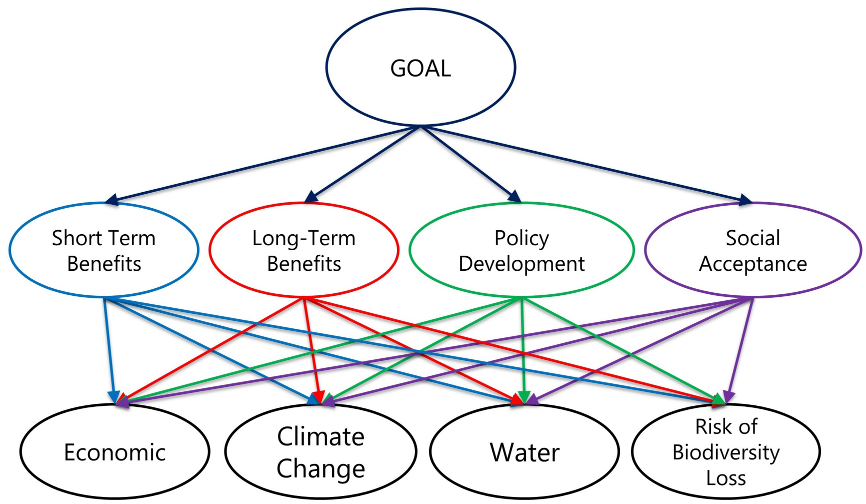


Figure 4: Decision structure for converting expert value judgment usingFAHP.

The overall procedure as described by the decision structure is explained as follows: First, the experts are required to evaluate two categories of pairwise comparison matrices: (1) pairwise judgment between impacts based on criteria and (2) pairwise comparison between these criteria. The first set of pairwise matrices allows the determination of priority weights for each impact based directly on qualitative expert judgment while the other set allows the determination of how important each criterion is according to the expert. The overall weights of each impact are then determined through Eq. (1).

$$w_i = \sum_k c_k s_{ik} \qquad \forall i \tag{1}$$

where s_{ik} is the priority weight of impact i with respect to criterion k and c_k is the importance of criterion k in relation to the overall goal in the decision structure. The weighted sum, w_i, is determined and used in the OPVC model. The criteria for expert judgment are described below. These are selected based on different factors that determines the importance of relevant value chain indicators such as profit and environmental damage.

- *Short-term benefits*: the impacts are evaluated based on the generated benefits of the value chain during its deployment and operation. The expert are asked to evaluate which of economic, climate change, water impacts or risk to biodiversity is more important when considering the development of the value chain and its perceived short-term benefits. This entails the decision on which factor should be prioritised depending on how they can affect the establishment of a strong value chain.
- *Long-term benefits*: the impacts are evaluated based on the generated benefits of the value chain when it becomes well established in the future. The experts are asked to evaluate which impacts should be prioritised considering the establishment of strong OPVCs in the future. This also involves how the value chain can affect the palm oil industry in the long term.
- *Policy Development*: the impacts are evaluated based on their importance in creating new economic and environmental policies. The prioritisation of different impacts in these criteria should also consider the

effect of the value chain in creating strategies for a more sustainable regulation in the palm oil industry. The experts should also consider how the model will generate insights to minimise environmental impacts while simultaneously obtaining reasonable economic benefits. This allows the model to provide useful information for policy development, such as whether to deploy technologies to valorise waste materials, to create strategies to minimise negative impacts from plantations and so on.

- *Social Acceptance*: the impacts are evaluated based on their overall acceptance and appeal to the public, especially when considering the decision to create an integrated palm oil value chain and the possible social benefits from it. This also involves giving priority to the factors that would promote positive social impact to the value chain. Experts should also consider the prioritisation based on generating a value chain that would promote sustainable oil palm products consumption. For instance, an expert could put more importance on biodiversity losses over economic benefits to allow consumers to have access to sustainable palm oil.

These criteria are the bases that affect the importance of considering different impacts generated by the value chain (i.e. economic benefits, climate change impact, water impact and biodiversity losses). For instance, the decision allows to determine whether the GHG emissions (i.e. climate change impact) is more important than economic benefits when it comes to developing future policies. The criteria used for the model can impact the results to align with the guidelines of RSPO Principles & Criteria (P&C) published June 2018 (RPSO, 2018) and MSPO Means of Compliance (MOC) published July 2019 (MSPO, 2019). These criteria can give more weights into minimising impacts that involve land use change through expansion (RSPO P&C 7.8.1, 7.8.5, and 7.12.1 and MSPO Means of Compliance 4.7) and to impacts that minimise water impact and GHG emissions (RSPO P&C 7.9 and 7.11 and MSPO MOC 4.5).The expert qualitative judgments are given as either "equally" (EQ), "slightly more" (SM), "moderately more" (MM), "strongly more" (ST), or "very strongly more" (VS) important than the other. The corresponding opposing qualitative judgment are denoted as 1/SM, 1/MM, 1/ST, and 1/VS for "slightly less", "moderately less", "strongly less" and "very strongly less" more important respectively. A sample pairwise comparison matrix with 3 alternatives is given in Table (1a). The equivalent quantitative judgment is given as triangular fuzzy numbers (TFN) of $< 1, 1, 1 >$, $< 1.2, 2, 3.2 >$, $< 1.5, 3, 5.6 >$, $< 3.0, 5, 7.9 >$ and $< 6.0, 8, 9.5 >$ for EQ, SM, MM, ST or VS judgments respectively. Their membership functions are described in Figure 5. These verbal judgments are highly unlikely to be equivalent to values from their upper bounds and above and from their lower bounds and below. The most likely numerical equivalent is given as their modal value and the likeliness increases towards it. Note that the gap between upper and lower bound widens as the judgment gets stronger. This is to account for large uncertainties when giving strong judgment between alternatives. These are based on the calibrated TFN's used to evaluate green technologies [45]. The calibrated scale was adopted from Promentilla et al. (2016) based on the calibration technique developed by Ishizaka and Hoang (2013). The technique captures experts judgment through qualitative analysis of alternatives with known measure and determine the equivalent TFNs based on the variation of responses. The TFN's represent the lower bound for the least possible equivalent of the qualitative judgment, the modal value for the most possible equivalent of the judgment and the upper bound for the least possible equivalent. Thus, the given example is converted as shown in Table (1b).

The priority weights are then derived using the optimisation model below with the objective of maximising λ (Eq. 2) which represents the overall consistency of the judgments in the pairwise comparison matrix subject

Table 1: Sample pairwise comparison matrix for 3 alternatives (A1, A2, A3) converted from verbal judgment (a) to TFN's (b)

(a)

	A1	A2	A3
A1	EQ	1/ST	1/SM
A2	ST	EQ	MM
A3	SM	1/MM	EQ

(b)

	A1	A2	A3
A1	$<1, 1, 1>$	$<0.13, 0.2, 0.33>$	$<0.31, 0.5, 0.83>$
A2	$<3, 5, 7.9>$	$<1, 1, 1>$	$<1.5, 3, 5.6>$
A3	$<1.2, 2, 3.2>$	$<0.18, 0.33, 0.67>$	$<1, 1, 1>$

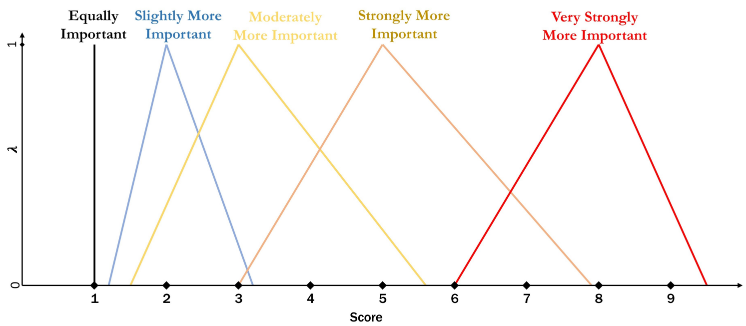


Figure 5: Graphical representation of the triangular fuzzy numbers and their membership function

to the membership functions of each fuzzy judgment:

$$\max \quad \lambda \tag{2}$$

$$a_{qq'} - \mathrm{l}_{qq'} \geq \lambda(\mathrm{m}_{qq'} - \mathrm{l}_{qq'})\,;\; a_{q'q} - \mathrm{l}_{q'q} \geq \lambda(\mathrm{m}_{q'q} - \mathrm{l}_{q'q}) \qquad \forall (q', q) | q < q' \tag{3}$$

$$\mathrm{u}_{qq'} - a_{qq'} \geq \lambda(\mathrm{u}_{qq'} - \mathrm{m}_{qq'})\,;\; \mathrm{u}_{qq'} - a_{q'q} \geq \lambda(\mathrm{u}_{qq'} - \mathrm{m}_{qq'}) \qquad \forall (q', q) | q < q' \tag{4}$$

$$a_{qq'} = w_q / w_{q'}\,;\; a_{q'q} = w_{q'} / w_q \qquad \forall (q', q) | q < q' \tag{5}$$

$$\sum_q w_q = 1 \tag{6}$$

This optimisation model solves the priority weights w_q from a given pairwise comparison matrix between a set of alternatives or criteria.These entries are expressed as triangular fuzzy numbers of $< \mathrm{l_{qq'}}\, \mathrm{m_{qq'}}\, \mathrm{u_{qq'}} >$ where $\mathrm{l_{qq'}}$is the lower bound, $\mathrm{m_{qq'}}$is the modal value and $\mathrm{u_{qq'}}$ is the upper bound for the expert judgment for alternative or criterion q with respect to another alternative or criterion q'in the pairwise comparison matrix. The non-fuzzy (crisp) judgment $a_{qq'}$ is described as the ratio between the priority weights of alternative q and q' and the set of these judgments are to be solved by the model to achieve the highest consistency. This model also allows incomplete judgment as long each alternative is involved in at least one judgment and there are at least $n - 1$ judgments, where n is the number of alternatives. Using the FPP model for the sample pairwise matrix in Table (1), the final weights for alternatives A1, A2 and A3 are 0.124, 0.647, and 0.229 respectively with $\lambda = 0.881$. This judgment shows consistency as it produces a degree of satisfaction, λ, close to 1.

4.2. Oil Palm Value Chain Model using Multi-Objective Optimisation

The objective function for the model is the weighted sum of the impacts from different components as shown in Eq. (7).

$$\min \sum_{i,p} \mathrm{w}_i \mathrm{NF}_i (IU_{i,p} + FIP^{\mathrm{OM}}_{i,p} + VIP^{\mathrm{OM}}_{i,p} + IP^{\mathrm{Cap}}_{i,p} + IT_{i,p} + II_{i,p} + IE_{i,p} + IL_{i,p} - R_{i,p}) \tag{7}$$

The index i denotes the type of impact (i.e $i \,\epsilon\, \{$Economic, Climate Change, Water, Biodiversity$\}$) by which the value chain is assessed.. The impacts are aggregated based on an arbitrary assignment of numerical weights denoted by w_i. Different objectives are enabled by setting the following weights for each objective function with corresponding units and the normalisation factor, NF_i, is obtained based on the best value of impact i.:

- Maximise profit (in million MYR): set $\mathrm{w}_{\mathrm{Economic}} = 1$, $\mathrm{w}_{\mathrm{Climate\,Change}} = 0$, $\mathrm{w}_{\mathrm{Water}} = 0$ and $\mathrm{w}_{\mathrm{Biodiversity}} = 0$.
- Minimise climate change impact (in Mt CO_2-equiv): set $\mathrm{w}_{\mathrm{Economic}} = 0$, $\mathrm{w}_{\mathrm{Climate\,Change}} = 1$, $\mathrm{w}_{\mathrm{Water}} = 0$ and $\mathrm{w}_{\mathrm{Biodiversity}} = 0$.
- Minimise water impact (in million m^3 H_2O): set $\mathrm{w}_{\mathrm{Economic}} = 0$, $\mathrm{w}_{\mathrm{Climate\,Change}} = 0$, $\mathrm{w}_{\mathrm{Water}} = 1$ and $\mathrm{w}_{\mathrm{Biodiversity}} = 0$.
- Minimise risks in biodiversity losses (in no. of species at risk): set $\mathrm{w}_{\mathrm{Economic}} = 0$, $\mathrm{w}_{\mathrm{Climate\,Change}} = 0$, $\mathrm{w}_{\mathrm{Water}} = 0$ and $\mathrm{w}_{\mathrm{Biodiversity}} = 1$.
- Expert-based objective (normalised to million MYR): ($\mathrm{w}_{\mathrm{Economic}}$, $\mathrm{w}_{\mathrm{Climate\,Change}}$, $\mathrm{w}_{\mathrm{Water}}$, $\mathrm{w}_{\mathrm{Biodiversity}}$) are evaluated using decision model in Section 4.1.

The last term in Eq. 7 ($R_{i,p}$) denotes the revenue generated from selling resources produced from the value chain. Note that this bears a negative sign to allow the model to maximise revenue generated while minimising other impacts. The terms in Eq. (7) are expressed as follows. The values are are calculated for each planning period p and each impact type i.

- Net present impact resulting from resource utilisation (i.e. generation of raw materials, acquisition of utilities outside the value chain, etc.):

$$IU_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{r,z,s,y} \mathrm{IUP}_{r,i,s,y,p} RU_{r,z,s,yp} \mathrm{n}^{\mathrm{sy}}_s \mathrm{n}^{\mathrm{yp}}_y \qquad \forall i,p \tag{8}$$

- Net present fixed impact resulting from the operation of conversion technologies:

$$FIP^{\mathrm{OM}}_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{c,z} \mathrm{FIPP}_{c,i,p} N_{c,z,s,y,p} \qquad \forall i,p \tag{9}$$

- Net present variable impact resulting from the operation of conversion technologies:

$$VIP^{\mathrm{OM}}_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{c,z,s,y} \mathrm{VIPP}_{c,i,p} Prod_{c,z,s,y,p} \mathrm{n}^{\mathrm{sy}}_s \mathrm{n}^{\mathrm{yp}}_y \qquad \forall i,p \tag{10}$$

- Net present capital impact resulting from investing new units of conversion technologies:

$$IP^{\mathrm{Cap}}_{i,p} = \varsigma \sum_{z} \mathrm{D}^{\mathrm{Prod}}_{c,i,p} \mathrm{IPP}^{\mathrm{Cap}}_{c,i,p} NI_{c,z,s,y,p} \qquad \forall i,p \tag{11}$$

- Net present impact resulting from transporting resources:

$$IT_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{b,r,r',s,y} (\mathrm{FIT}_{t,r,i,p} + \mathrm{DDIT}_{t,r,i,p}\mathrm{AD}_{b,z,z'}) TR_{t,r,z,z',s,y,p} \mathrm{n}^{\mathrm{sy}}_{s} \mathrm{n}^{\mathrm{yp}}_{y} \qquad \forall i, p \tag{12}$$

- Net present impact resulting from importing resources:

$$II_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{r,z,s,y} \mathrm{IIP}_{r,i,p} RI_{r,z,s,y,p} \mathrm{n}^{\mathrm{sy}}_{s} \mathrm{n}^{\mathrm{yp}}_{y} \qquad \forall i, p \tag{13}$$

- Net present revenues resulting from selling resources:

$$R_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{r,z,s,y} \mathrm{Price}_{r} \mathrm{D}_{r,z,s,y,p} \mathrm{D}^{\mathrm{min}}_{r} \mathrm{n}^{\mathrm{sy}}_{s} \mathrm{n}^{\mathrm{yp}}_{y} \qquad \forall i = Economic, p \tag{14}$$

- Net present impact resulting from exporting resources:

$$IE_{i,p} = \varsigma \mathrm{D}^{\mathrm{OM}}_{i,p} \sum_{r,z,s,y} \mathrm{EP}_{r} RE_{r,z,s,y,p} \mathrm{n}^{\mathrm{sy}}_{s} \mathrm{n}^{\mathrm{yp}}_{y} \qquad \forall i = Economic, p \tag{15}$$

- Net present impact resulting from additional land for oil palm plantations:

$$IL_{i,p} = \sum_{b,z} \mathrm{ILP}_{i,z,p} AI_{b,z,p} \qquad \forall i = Biodiversity, p \tag{16}$$

The impact components in the value chain are discussed as follows. Eq. (8) shows the net impact from utilisation of resources in which the total impact is proportional to the rate of resource utilisation ($RU_{r,z,s,y,p}$). The unit utilisation impact ($\mathrm{IUP}_{r,i,s,y,p}$) denotes the price for acquiring the raw materials, or its carbon and water footprints. Eqs. (9), (10) and (11) show the impacts related to resource production and are proportional to the number of conversion units ($N_{c,z,s,y,p}$), rate of operation ($Prod_{c,s,z,,y,p}$) and number of conversion units invested ($NI_{c,z,s,y,p}$), respectively. These correspond to the capital and operating costs of the resource production and environmental footprint generated during production. Eq. (12) denotes the impact from transportation, dependent on both the amount of resource transported and transportation distance. Eq. (13) denotes the impact of importing resources outside the region of interest. For instance, a specific region may require to obtain biomass resources outside when it is cheaper or has a less carbon footprint due to presence of more efficient technology. Eq. (15) denotes the impact resulting from the export of resources in which the optimal export levels are determined. In this case, only economic factors are considered for the value chain, since environmental impacts are assumed to occur outside of the value chain boundary. Eq. (14) pertains to the revenue of the value chain, which is dependent on the price of the resources and the satisfied demand. The impact of plantation expansion can be estimated in the value chain through Eq. (16) which requires a spatial indicator ($\mathrm{ILP}_{i,z,p}$) for biodiversity such as local species richness.

The discounting factor $\mathrm{D}^{\mathrm{OM}}_{i,p}$ converts the impacts into net present equivalent and this is expressed based on the interest rate f. It is an element of "discounted cash-flow analysis", which aims to account for the time-value of money. A discount factor is used to evaluate the present value of a future cash flow, and summing all present values of future cash flows results in the Net Present Value, which is a standard measure of an investment's performance. A good estimate of the discounting factor is to divide the total impact into equal payments to be assigned at the end of each year into the planning period. Then, the second factor in Eq.

(17) calculates the discounted factor at the beginning of the planning period and then the net present worth is calculated using the third factor in Eq. (17).

$$\mathrm{D}_{i,p}^{\mathrm{OM}} = \frac{1}{\Delta\mathrm{T}}\left[\frac{(1+\mathrm{f})^{\Delta\mathrm{T}}-1}{(1+\mathrm{f})^{\Delta\mathrm{T}}\mathrm{i}}\right]\left[(1+\mathrm{f})^{\Delta\mathrm{T}(1-\mathrm{p})}\right] \tag{17}$$

The capital discounting factor $\mathrm{D}_{c,i,p}^{\mathrm{Prod}}$ is expressed based on the finance rate jand the interest rate f. The capital cost for a technology, which can operate for T_c years, is annualised based on the finance rate to be paid each year until its estimated end of life and to be discounted based on the interest rate.

$$D_{c,i,p}^{\mathrm{Prod}} = \left[\frac{(1+\mathrm{f})^{\mathrm{T}_c}-1}{(1+\mathrm{f})^{\mathrm{T}_c}\mathrm{f}}\right]\left[\frac{(1+\mathrm{j})^{\mathrm{T}_c}\mathrm{j}}{(1+\mathrm{j})^{\mathrm{T}_c}-1}\right]\left[(1+\mathrm{i})^{\Delta\mathrm{T}(1-p)}\right] \tag{18}$$

The overall resource balance is expressed in Eq. (19). The demand for each resource r, in zone z at month type s, in year type y, and planning period p is satisfied based on the net sum of resources from utilisation ($RU_{r,s,z,y,p}$), production ($RP_{r,z,s,y,p}$), transportation ($RT_{r,z,s,y,p}$), and import ($RI_{r,z,s,y,p}$). The left hand-side of the constraint pertains to the net flow of resource r, at zone z in month type m, in year y in planning period p. This results from the acquisition of a resource (i.e. utilisation) within the planning region ($RU_{r,z,s,,yp}$), production (or consumption) of the resource ($RP_{r,z,s,,y,p}$), transportation of the resource in and out of zone z ($RT_{r,z,s,y,p}$) and import of resources from outside the planning region ($RI_{r,z,s,y,p}$). The net flow of resource is used to satisfy both the resource demand and the export duty.

$$RU_{r,z,s,y,p} + RP_{r,z,s,y,p} + RT_{r,z,s,y,p} + RI_{r,z,s,yp} \geq \mathrm{D}_{r,z.s,y,p}(\mathrm{D}_r^{\min}) + RE_{r,z,s,y,p} \qquad \forall r,z,s,y,p \tag{19}$$

Planning for the value chain requires the satisfaction of a certain fraction ($\mathrm{D}_r^{\min}$) of the demand, $\mathrm{D}_{r,z,s,y,p}$ and the satisfaction of the export duties by the value chain. The inequality constraints means that the net resources can exceed the minimum fraction of demand which happens when technologies need to be operating at a minimum capacity and the amount of products exported.

One of the unique features of the optimal OPVC model is its capability to incorporate decisions for land expansion of oil palm plantation based on its yield in each season and in its life cycle. Eq. (20) limits the availability of resource b in zone z in season s, year y and planning period p.

$$RU_{b,z,s,y,p} \leq \mathrm{AE}_{b,z}\mathrm{YFE}_p\mathrm{Y}_{b,z,s,y} + \mathrm{Y}_{b,z,s,y}\sum_{p'}\mathrm{YF}_{p,p'}AI_{b,z,p'} \qquad \forall b,z,s,y,p \tag{20}$$

The first term in the right-hand side of the constraint in Eq. (20) denotes the available raw materials produced from existing plantations while the second term denotes the raw materials produced from additional land included due to expansion at planning period p. The base yield $\mathrm{Y}_{b,z,s,y}$ denotes the yield of fresh fruit bunch for a particular month type s and year type, y. The average yield of an existing plantation in planning period p is given by the factor YFE_p which also denotes the age of the plantation. Replanting can also be considered in some regions in which the existing plantation, if replanted will have a yield factor (YFE_p) of 40% of its peak yield and the succeeding four periods will have a yield factor equal to its peak yield. The limit on the availability of a raw material is determined by the seasonal and cyclical yield, the existing plantation area and the area available for expansion. The decision for expansion is denoted in the second term of the right-hand side of the constraint. This involves how much land, $AI_{b,z,p'}$ is invested at planning period p' and the yield factor $\mathrm{YF}_{p,p'}$ denotes the yield of this land at planning period p'. The yield factor is illustrated in Table (2). This is based on a typical life-cycle of oil palm, in which the yield gradually increases for the first

Table 2: Yield factor for planning period p for lands planted at planning period p'

	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
2015-2020	0.4	1	1	1	1	0.9	0
2021-2025		0.4	1	1	1	1	0.9
2026-2030			0.4	1	1	1	1
2031-2035				0.4	1	1	1
2036-2040					0.4	1	1
2041-2045						0.4	1
2046-2050							0.4

5 years and reaching its peak for 20 years (1). For instance, new land cultivated in the period of 2026-2030 will have an average yield of 40% of its peak yield and it will generate its maximum yield at from 2031 to 2050. For land planted as early as 2021, the yield declines at the end of 2050 and it needs to be replanted after that period.

The decision for new plantations is optimised based on the life cycle of oil palm. The constraint for oil palm expansion is expressed on a local in Eq. (21) and national basis in Eq. (22).

$$\sum_{p'|p'<p} AI_{b,z,p'} + \mathrm{AE}_{b,z} \leq \mathrm{A}^{\mathrm{lmax}}_{b,z,p} \qquad \forall b,z,p \tag{21}$$

$$\sum_{z} AI_{b,z,p} \leq \mathrm{A}^{\mathrm{gmax}}_{b} \qquad \forall b,p \tag{22}$$

The utilisation of resources in the value chain is bounded by a maximum value $\mathrm{RU}^{\max}_{r,z,s,y,p}$ as shown in Eq. (23). For resources such as heat and electricity which can be purchased outside the value chain, this parameter is non-negative. Otherwise, if the resources needs to be produced within the value chain, the value is set to 0.

$$RU_{r,z,s,y,p} \leq \mathrm{RU}^{\max}_{r,z,s,y,p} \qquad \forall r,z,s,y,p \tag{23}$$

The rate of production of resources, $RP_{r,z,s,y,p}$ is given by the production level $Prod_{c,z,s,y,p}$ multiplied by the conversion factor $\mathrm{Conv}_{c,p,r}$. The formulation of the constraint in Eq. 24) is based on input-output approach wherein $\mathrm{Conv}_{c,p,r}$ denotes the amount of resource r that can be produced by technology c at a given planning period p and $Prod_{c,z,s,y,p}$denotes the scaling factor of the technologies.

$$RP_{r,z,s,y,p} = \sum_{c} Prod_{c,z,s,y,p} \mathrm{Conv}_{c,p,r} \qquad r,z,s,y,p \tag{24}$$

The production level is bounded based on the number of conversion units $N_{c,z,p}$ at zone z in planning period p and the minimum $\mathrm{Prod}^{\min}_{c}$and maximum $\mathrm{Prod}^{\max}_{c}$ levels of production per conversion unit:

$$N_{c,z,p}\mathrm{Prod}^{\min}_{c} \leq Prod_{c,z,s,y,p} \leq N_{c,z,p}\mathrm{Prod}^{\max}_{c} \qquad \forall c,z,s,y,p \tag{25}$$

The nominal design of the value chains assumes that the conversion units are operating throughout its lifetime, thus a minimum production level is assumed when all production units are running. This is to maximise the value of the investment for conversion technologies. To account for the retirement and investment of technologies in the planning horizon, Eq. (26) expressed the total number of conversion units in terms of existing, invested, and retired conversion units. The decision variable is denoted by the number of conversion

Table 3: Retirement factor for a technology with 10-year lifetime

	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
2015-2020			1				
2021-2025				1			
2026-2030					1		
2031-2035						1	
2036-2040							1
2041-2045							
2046-2050							

units invested at a given planning period, $NI_{c,z,p}$.

$$N_{c,z,p} = \begin{cases} \mathrm{NE}_{c,z,p} + NI_{c,z,p} - NR_{c,z,p} - \mathrm{NER}_{c,z,p} & \text{if} p = 1 \\ N_{c,z,p-1} + NI_{c,z,p} - NR_{c,z,p} - \mathrm{NER}_{c,z,p} & \text{if} p \neq 1 \end{cases} \qquad \forall c, z, p \tag{26}$$

The total number of conversion units that can be invested in is limited to its build rate, $\mathrm{BR}_{c,p}$ at any given planning period p.

$$\sum_{z} NI_{c,z,p} \leq \mathrm{BR}_{c,p} \qquad \forall c, p \tag{27}$$

The retirement of conversion units in a particular planning period p is determined by its retirement factor, $\mathrm{RF}_{c,p,p'}$, a binary parameter indicating the retirement of a technology at planning period p invested at planning period p'. This is illustrated in Table (3) using an example of a technology with a 10 year lifetime. For instance, if the technology is invested in the period of 2015-2020, it is expected to retire in the period of 2026-2030. The retirement factor is analogous to that of the yield factor except that it only accepts binary values denoting the retirement of the technology. This is applicable to all technologies in the value chain including small-scale and large-scale palm oil mills.

$$NR_{c,z,p} = \sum_{p'} \mathrm{RF}_{c,p,p'} NI_{c,z,p'} \qquad \forall c, z, p \tag{28}$$

The net rate of transport of resources is expressed in Eq. (29). The first term of Eq. (29) denotes the total incoming resource flow from all other zones z' and transport infrastructure t while the second term indicates the total outgoing flows from zone z' and transport infrastructure t.

$$RT_{r,z,s,y,p} = \sum_{t,z'} TR_{t,r,z,z',s,y,p} - \sum_{t,z'} TR_{t,r,z',z,s,y,p} \qquad \forall r, z, s, y, p \tag{29}$$

The rate of transport of resources is constrained by the capacity of transport infrastructure ($\mathrm{T}^{\max}_{\mathrm{t,r}}$). The binary parameter $\mathrm{b}_{\mathrm{t,z,z'}}$ indicates the presence of the transport infrastructure t between zones z and z'.

$$TR_{t,r,z,z',s,y,p} \leq \mathrm{T}^{\max}_{t,r} \mathrm{b}_{t,z,z'} \qquad \forall t, r, z, z', s, y, p \tag{30}$$

The rate of import of resources is limited by a maximum amount denoted by $\mathrm{RI}^{\max}_{r,s,y,p}$. This constraint enables to model to control the amount of resources needed to be imported and forces the production of resources within the value chain instead.

$$\sum_{z} RI_{r,z,s,y,p} \leq \mathrm{RI}^{\max}_{r,s,y,p} \qquad \forall r, s, y, p \tag{31}$$

The rate of export of resources is bounded between the minimum export duty and the maximum amount. This constraint allows to determine how much of the export duty can be attained from the current production level.

$$\mathrm{RE}^{\min}_{r,y,p} \leq \sum_{z,s} RE_{r,z,s,y,p}\mathrm{n}^{\mathrm{sy}}_{s} \leq \mathrm{RE}^{\max}_{r,y,p} \qquad \forall r, y, p \tag{32}$$

$$\mathrm{RE}^{\min}_{r,y,p} = \mathrm{RE}^{\mathrm{duty}}_{r,y,p}\mathrm{E}^{\min}_{r,y,p} \qquad \forall y, p \tag{33}$$

The export level can be adjusted to range from a user-defined minimum denoted in Eq. (33) and the maximum level $\mathrm{RE}^{\max}_{r,y,p}$. This is to ensure that whenever the export duty, $\mathrm{RE}^{\mathrm{duty}}_{r,y,p}$, is not achievable due to production constraints, the user can set a minimum threshold, $\mathrm{E}^{\min}_{r,y,p}$ which can be adjusted in order to obtain a feasible solution.

The model with an objective function expressed in Eq. (7) subject to constraints in Eqs. (8) to (33) is solved. The model is implemented in AIMMS software running in a PC with a 2.70 GHz processor and 16 GB of RAM. Computational times for the model ranges from 1 min to 30 mins. The following section discusses the case study to apply for the Malaysian palm oil industry. The model is applicable not only to Malaysia's palm oil industry but also to other countries/regions as well as to other value chains. The cases involve maximum economic benefits for a business-as-usual case subject to issue on further expansion of plantation area for the first case and expert-based approach to maximise both economic and environmental benefits.

5. Malaysia's Palm Oil Industry Case Study

The integrated model developed in Section 4 is used to examine different scenarios for the Malaysian oil palm industry. There are two cases considered: maximum economic benefits from the value chain and expert-based solution using the value judgment given by experts in Malaysia. For the first case, the scenario wherein the current plantation is allowed to be expanded is also considered in addition to a scenario with gradual expansion. A sensitivity analysis is performed examining the effect of different cuts of crude palm oil (CPO) export duty. For the second case, an expert-based optimal solution is obtained to demonstrate the trade-offs between economic and environmental impacts. The model decides the number of technology to be invested in each region and the production levels for each technology. From these decisions, the model calculates the economic benefits and environmental impacts arising from the optimal solution.

The value chain pathway considered for the study is shown in Figure 6. Three major palm-based biomass types are considered for conversion into energy and material products, namely: EFB, POME and PKS. EFB is the most flexible in terms of potential pathways for conversion but pre-treament is required for it to be converted into energy products such as syngas and bio-oil through gasification and pyrolysis. It is then converted into transportation fuels through Fischer-Tropsch synthesis and bio-oil upgrading. Among the biomass produced from oil palm, PKS has the highest calorific value (Onochie Uche et al. [50]), which is its main advantage over PMF, although both biomass have limited technological options in the value chain. Electricity and heat are generated through cogeneration (direct combustion) of either PKS or EFB. Other pathways considered include converting palm-based syngas into hydrogen and then, by using solid oxide fuel cells (SOFC), convert it to electricity and heat. The pathways for conversion of POME are: anaerobic digestion to produce biogas, microbial fuel cell to produce electricity, composting to produce biocompost and

Table 4: Optimisation model sizes and computational times for Malaysia's palm oil industry case

Case	Number of Constraints	Number of Variables	Computational Time (s)
Maximum Profit (Case 1)	166,225	167,156 (3990 integers)	300 to 450
Expert-based Multi-objective (Case 2)	166,382	167,313 (3990 integers)	20 to 40

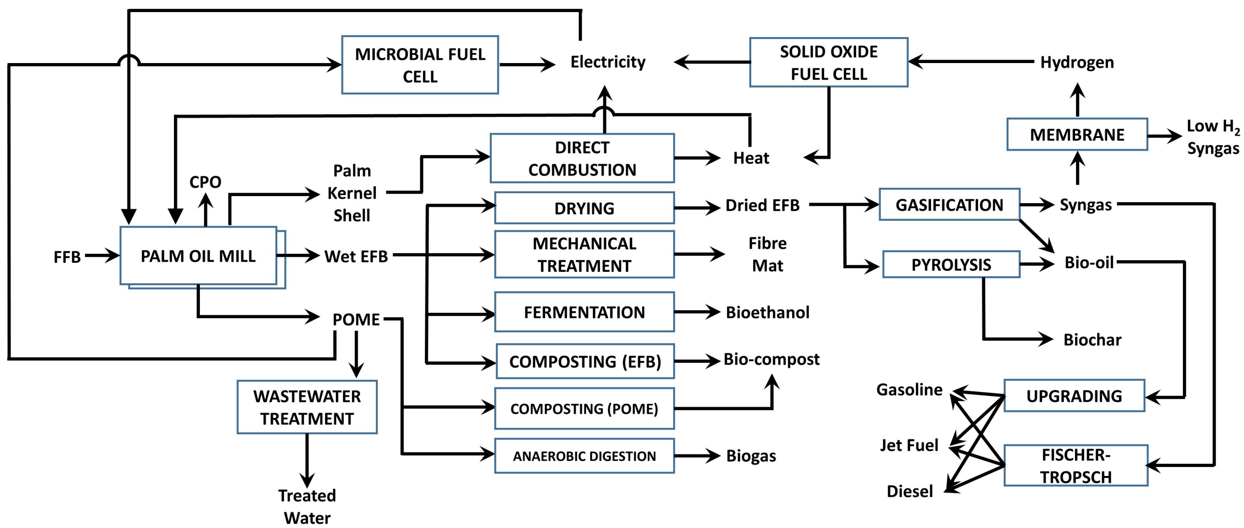


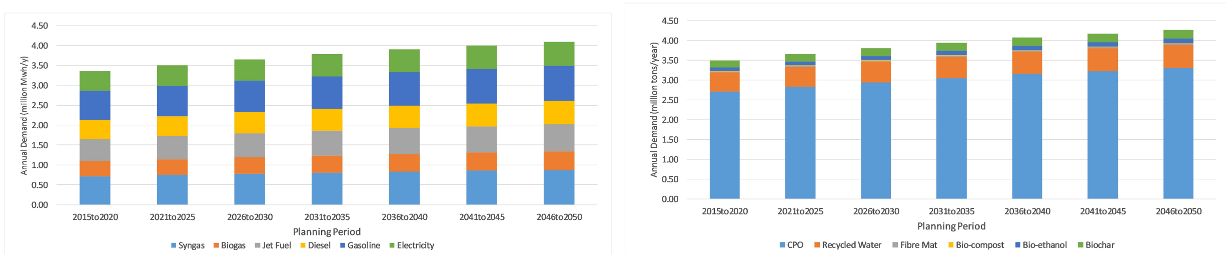
Figure 6: Value web pathway considered for oil palm and its biomass by-products: EFB, POME and PKS

wastewater treatment to produce treated water. For generation of biocompost from POME, the technology used involves co-composting with EFB as described by Krishnan et al. [51]. Materials, such as fibre mat, are also included in which the technology is based from biocomposite technology described by Abdulrazik et al. [25]. From these pathways, electricity is produced by three technologies and is used to power palm oil mills. This allows provision of additional energy to run the palm oil mills as well as satisfaction of a portion of the customer's demand.

The set of demands for valuable products is summarised in Fig 7. This is based on the range of energy products provided by Abdulrazik et al. [25]. Here, the major demands to satisfy are electricity, heat and transportation fuels (i.e. gasoline, jet fuel and diesel). The future demand was based on the population projection by Abdullah [52] on the assumption that consumption patterns remains constant. In the value chain framework, the total product demand for Peninsular Malaysia is partially satisfied; the objective of the value chain model is to determine the best value or the minimum negative impact generated by satisfying a portion of the total demand. A summary of the computational times and optimisation model sizes are shown in Table 4. The use of the normalisation factor for the multi-objective case (Case 2) and the smaller weight for the objective of maximum economic benefits allows the model to approach the optimal value faster than the single objective case (Case 1).

5.1. Case 1: Maximum Economic Benefit With and Without Expansion of Oil Palm Plantation

This case discusses the scenarios in which the maximum economic benefit is maximised with and without expansion of oil palm plantation. The plantation is assumed to expand only up to the available immature



(a) (b)

Figure 7: Demand curves to satisfy for the case studies. (a) energy products (b) CPO and material Products

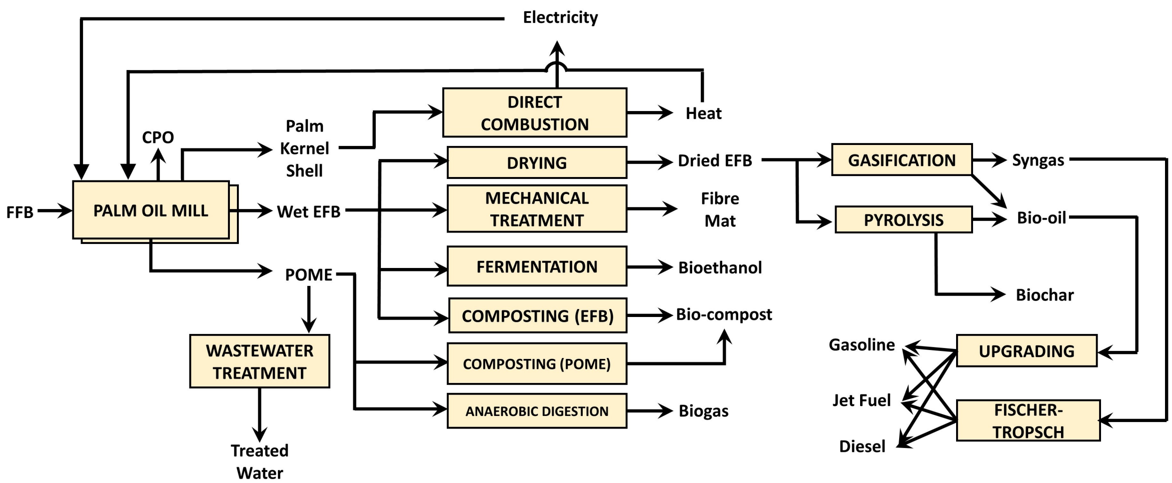


Figure 8: Optimal value web pathway for Malaysian OPVC

plantations (MPOB, 2018). On the other hand, the scenario in which the expansion is not allowed only uses the current oil palm plantations. The insights gained from this case study are the changes in palm oil production, the staged investments done to convert palm-based biomasses into energy products and most importantly, the effect of the scenarios in satisfying the export demand of CPO that Malaysia needs to satisfy. This will suggest policies for a sustainable palm oil industry. The optimal value web for the case study is shown Figure (8). Electricity and heat are being produced through direct combustion of PKS. This eliminates the need for investing into high-costs fuel cell technologies (i.e. microbial fuel cell and solid oxide fuel cells) to satisfy demand for electricity and heat.

Figure 9 shows the demand satisfied for crude palm oil (CPO) and the export duties attained in each time period when the plantation expansion is allowed in Peninsular Malaysia. The minimum fraction of export duty satisfied for this case is assumed to be at 60%, which is a safe assumption to obtain a feasible solution. Based on the results, the current plantation and the available land for expansion (i.e. non-mature plantations) can still achieve its export duty until the end of 2030, after which there is a need to take actions in order to be able to achieve the projected export duty. At the end of the planning period, the total plantation including the expanded land available can only achieve 73% of the minimum export duty. The plantation in Peninsular Malaysia can still satisfy their domestic demand during the whole planning horizon. The amount exported from the Peninsular Malaysia can rise up to 9.6 million tons of CPO per year, achieved during the period of 2031 to 2035, and it slowly declines due to increasing domestic demand. Overall, there is a significant time to develop ways for sustainable vegetable oil industry given the time that the current plantation in Peninsular Malaysia can still achieve its export duties is up to 11 years (2030). In this case study, the effect of improving the yield of palm oil plantation is analysed using the integrated model.

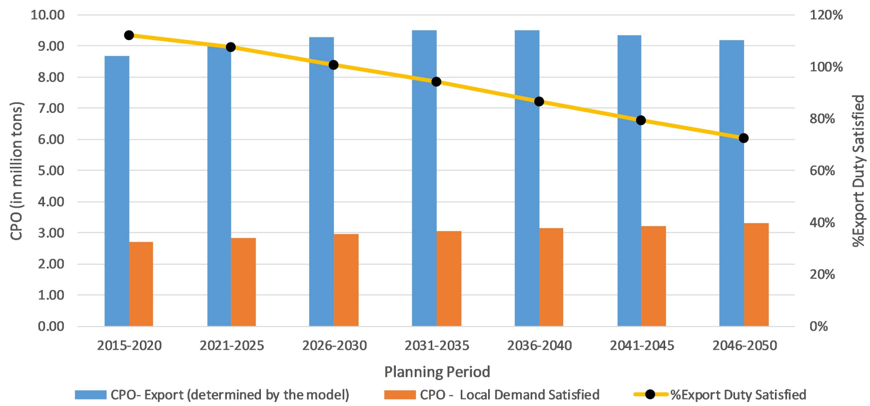


Figure 9: Optimal solution for CPO demand and export satisfaction when plantation expansion is allowed

The share of small- and large-scale palm oil mills and their production rates are shown in Figure 10. Small scale POMs have a capacity of up to 1000 ton/month of CPO while large-scale POMs are assumed to produce from 1000 ton/month up to 4000 ton/month, based in typical regional production capacities in Peninsular Malaysia (MPOB,2018). The three regions, namely, Perak, Pahang and Johor, produces the highest amount of crude palm oil due to its large plantation sizes. The investment of small-scale POMs in Penang is recommended and regions such as Perak, Selangor, and Melaka also invests in small-scale plantations until 2050. Large-scale plantation is dominant in the region to minimise capital cost requirements. The growth in CPO production in each region is proportional and is very dependent to the availability of the oil palm plantations.

Energy products in Peninsular Malaysia are generated based on the conversion technologies as shown in Figure 11. Electricity is produced mainly in the region primarily because of the required electricity to run palm oil mills. A big share of production of electricity is contributed in Johor in which more than 70% of the energy products generated is in the form of electricity. Despite the large generation of palm-based biomass in Pahang, the size of production of energy products is smaller than Perak and Johor. This is due to the transportation infrastructure allowing the transfer of energy products such as diesel and gasoline into the region.The investment of conversion technologies is also dependent on the demand rather than the production levels since the available palm-based biomass generated from satisfying domestic demand is enough to satisfy the required energy demand in each region. Based on the investment of technologies in Figure 11, cogeneration units have the highest investment in terms of number. It is also noted that energy products in Selangor are also increased throughout the planning horizon. The optimal staged investment and production levels suggests that there is a huge potential for the palm-based biomass to contribute to the increasing energy demand in Malaysia.

Considering the scenario in which the oil palm plantation is allowed, Figure 12 shows the optimal decision in the expansion of oil palm plantation. Most of the regions are required to increase their plantations, ranging from 2% up to 12% to be able to satisfy the demand for crude palm oil, both domestically and internationally. Regions such as Kelantan, Negeri Sembilan and Terengganu are suggested to delay plantation expansion,

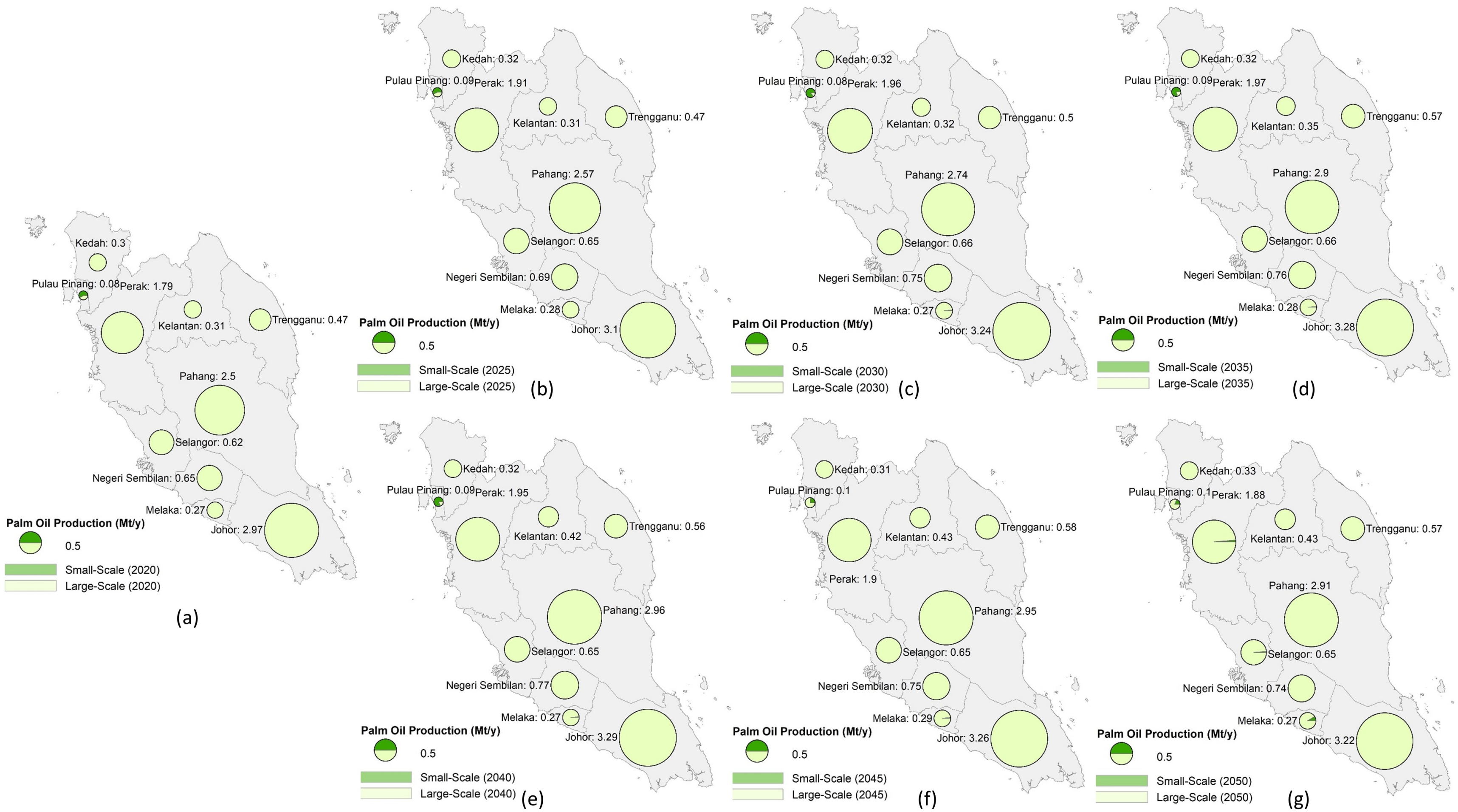


Figure 10: Palm oil production in Peninsular Malaysia in different planning periods: (a) 2015-2020 (b) 2021-2025 (c) 2026-2030 (d) 2031-2035 (e) 2036-2040 (f) 2041-2045 (g) 2046-2050

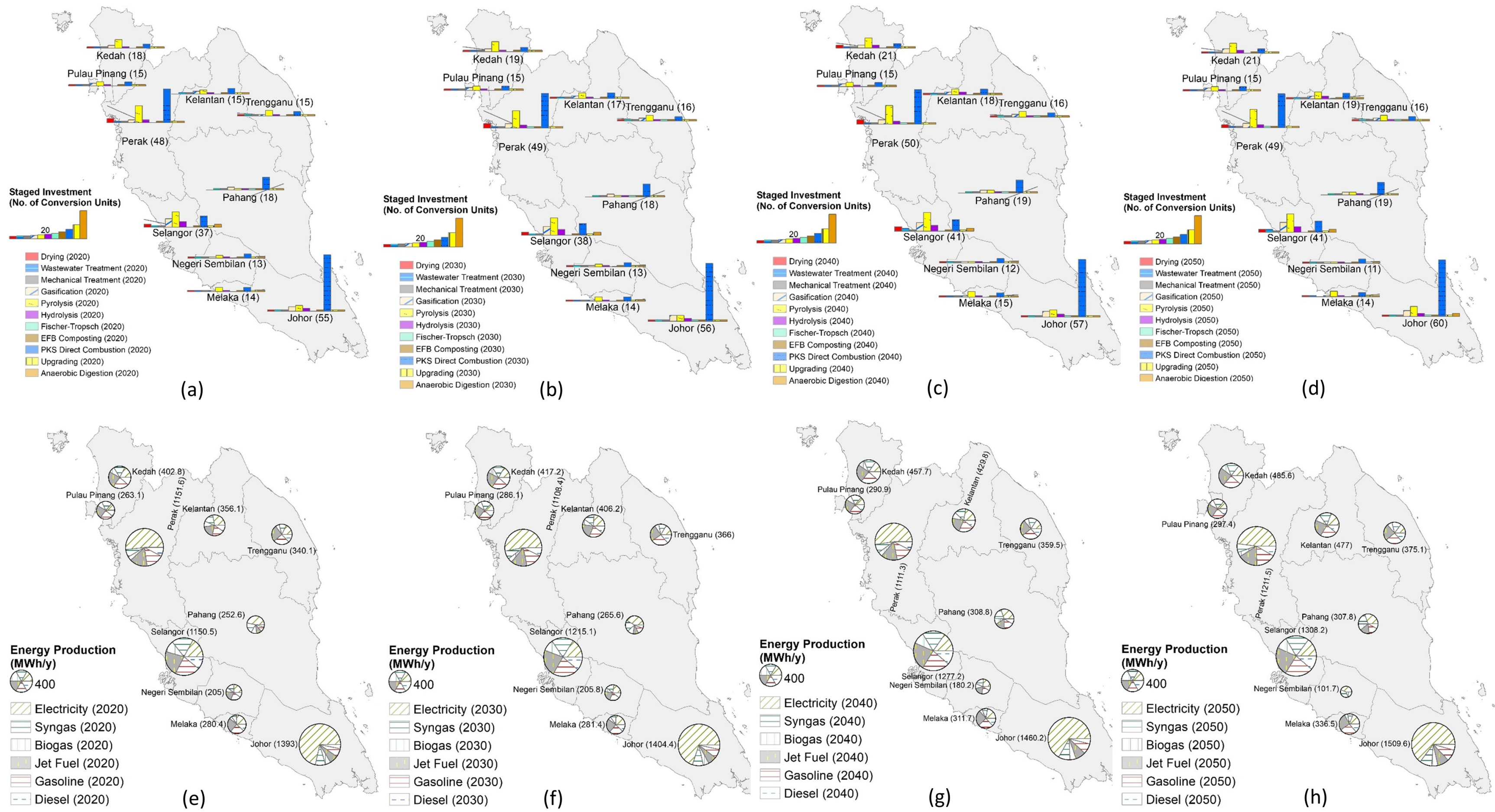


Figure 11: Staged investment for (a) 2015-2020 (b) 2021-2030 (c) 2031-2040 and (d) 2041-2050 in number of conversion units and annual energy products generation for (e) 2015-2020 (f) 2021-2030 (g) 2031-2040 and (h) 2041-2050 in '000 MWh/y.

especially Kelantan in which the decision for expansion is made at the beginning of 2026. The Peninsular Malaysia, having a total area of 2.24 million ha of oil palm plantation is expanded up to 2.7 million ha in 2050, having a total increase in plantation area of 20%. Note that the region with the highest expansion to attain at least 70% of the minimum export requirement in 2050 is Kelantan, which expands by 34%. The expansion allowance in this study is based on immature plantations available [53], actual conversion of agricultural land is restricted in this case study. However, suitable land can be identified using GIS-based land suitability approach considering biophysical characteristics (55). In this case, the expansion decision is considered to potentially avoid further negative environmental impacts by using availables areas not classified as forest, peatlands or any existing land use. Based on this result, it can be inferred that in order to maximise economic benefits, Peninsular Malaysia may need to increase its plantation early in the planning horizon to be able to allow the plantation to mature and be able to attain the required yields and production.

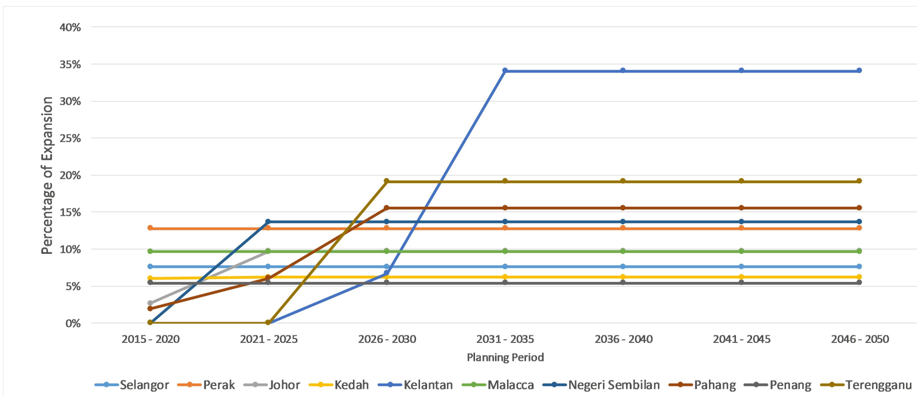


Figure 12: Optimal palm oil plantation expansion

The production costs for the value chain are summarised in Figure 13. This is obtained from the combined capital impact in Eq. (11), fixed operating impact in Eq. (9) and variable operating impact in Eq. (10) for each technology. The costs for the value chain come mainly from the operation of palm oil mills and investment into new large-scale palm oil mills. The investment for pyrolysis units is significant as it is used mainly to satisfy demands for biochar and bio-oil for further upgrading into transport fuels. Power generation also contributes significantly to the cost of the value chain as it is required to satisfy demands for electricity and supply electricity within the value chain. The cost distribution also implies that a significant portion of investment goes into gasifiers to produce additional materials to satisfy demands for transportation fuel. The total production costs amount to 63 billion MYR throughout the 35-year planning period of the oil palm value chain in Peninsular Malaysia.

To offset the costs for the value chain and to generate economic benefits, the resulting revenues from satisfying the domestic consumption of high-value products generated by the value chain is shown in Figure (14). This is calculated based on Eq. (14) for each resource in the value chain. A major portion of the revenue is generated from selling of crude palm oil, which is 85% of the total revenue generated amounting to 167 billion MYR while the total revenue generated from exporting crude palm oil amounts to 461 billion MYR. The revenues from transportation fuels generated from the value chain constitute 6.5% of the total revenue while the energy products contribute 11% of the total revenue domestically. The value chain implies that if the demand and export duty for crude palm oil are satisfied then the production of high-value products

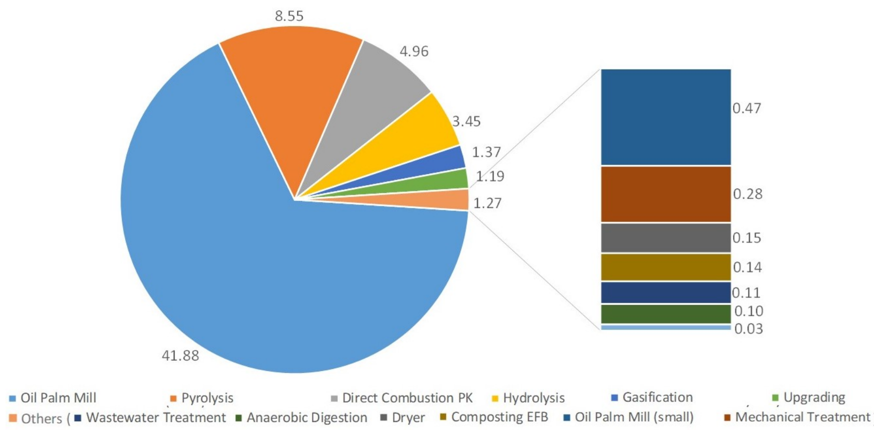


Figure 13: Production costs for different conversion technologies (in billion MYR)

from its biomass will be profitable. This is also demonstrated in the results of Abdulrazik et al. [25].

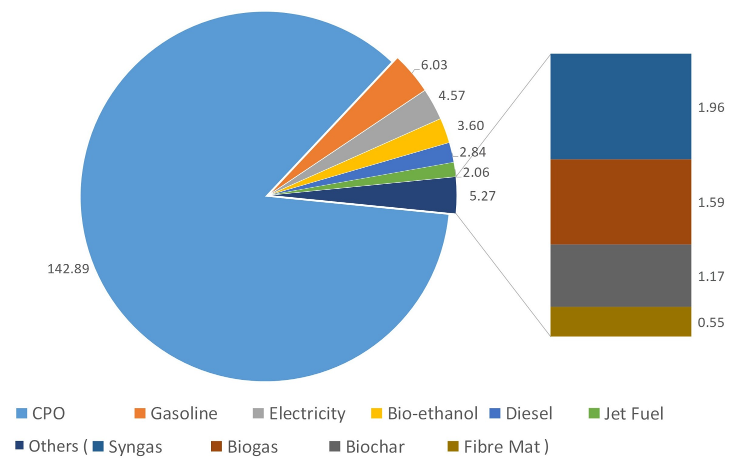


Figure 14: Revenue shares of valuable products generated in the value chain (in billion MYR)

Considering the scenario in which the plantation expansion is not allowed, Figure (15) summarises its effect on export duty and demand satisfaction of crude palm oil. It is noted that without further expansion of the plantation, the export duties should be cut by 40% in 2045 and the export of crude palm oil starts to drop gradually from 8.56 to 7.96 million ton/year resulting in a 7% decrease of annual export duty satisfaction. The demand for crude palm oil is still satisfied domestically and the products derived from palm biomasses are also generated. The total economic benefits also drop from 473 billion MYR when expansion is allowed to 433 million MYR. This implies that a small cut in the economic benefits allows the risks of biodiversity losses to be minimised to insignificant levels. Best practices can still be employed to increase the yield of palm oil and satisfy the required export duty.

In order to determine the required improvement in FFB yield, a sensitivity analysis was performed by setting yield improvements starting the period of 2026-2030. These were set from an initial yield-improvement of 10% to an improvement that satisfies the projected CPO export duties of 55%. The yields from the first two planning period were not changed since both periods still attain their minimum export duty. The analysis

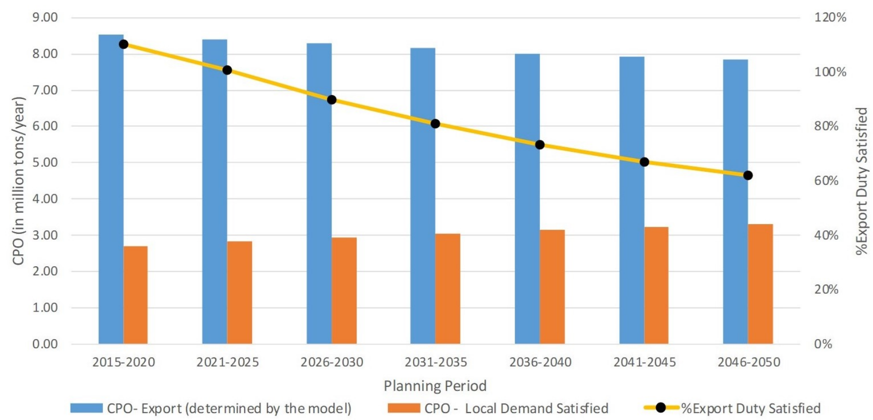


Figure 15: CPO demand and export satisfaction when plantation expansion is not allowed

also implies that the gradual improvements in yield can attain minimum export duties of CPO in which 10% improvement is required in every planning period, increasing from 10% at the beginning of 2021 to 50% at the end of 2050. This improvement does not require expansion of oil palm plantations and thus, risks in biodiversity losses and greenhouse gas emissions due to land use change are insignificant.

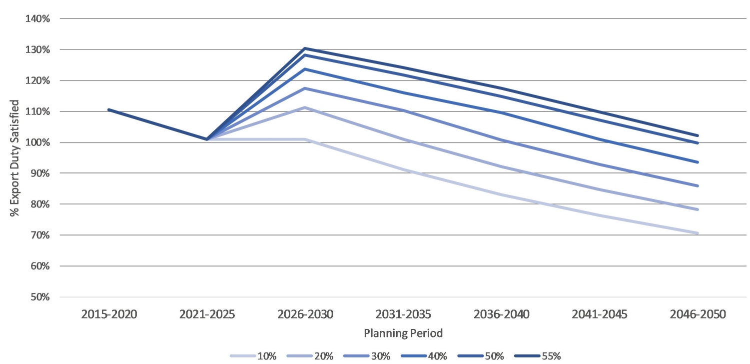


Figure 16: Sensitivity analysis with different levels of yield improvements of FFB

Table 5 summarises the current yield set in the model (adapted from MPOB [2018]) and the required yield improvement to satisfy CPO production requirements. The theoretical yield of more than 8 tons CPO/ha/y is ideal based on perfect crop management practices considering yield-determining factors such as planting density, culling and pruning practices and environmental conditions. These factors are based from the study examining the yield gaps in palm oil [57]. The range of yield necessary for the palm oil mills is from 3.8 ton CPO/ha/y to 7.0 ton CPO/ha/y. From Figure (16), the required annual yield to be analysed is 50% more than the current average yield. Based on the theoretical yield (Woittiez et al. 57), the required yield is still attainable for all the regions. On the other hand, based on the nutrient/water limited yield of 6.1 ton CPO/ha/y, 5 regions failed to attain the required yield which represents 37.8% of the total production. Thus, necessary actions to increase the yield is sufficient to satisfy future global demand supplied from Peninsular Malaysia without the need to further expand oil palm plantations and pose risks in biodiversity losses and greenhouse gas emissions due to land use changes. It may be challenging to implement region-wide best management practices, however, gradual improvements can still be applied to minimise environmental impacts from palm oil industry.

Table 5: Current yield and required yield of FFB in order to satisfy their export duty until the end of planning horizon

Region	**Current Average Yield (ton CPO/ha/y)**	**Required Yield (ton CPO/ha/y)**
Johor	4.132	6.404
Kedah	3.771	5.845
Kelantan	2.512	3.894
Malacca	4.557	7.063
Negeri Sembilan	3.884	6.021
Pahang	3.714	5.756
Perak	4.531	7.024
Penang	3.753	5.817
Selangor	4.527	7.017
Terengganu	3.090	4.790

Based on the results of this case study, the following insights are made:

- The level of export duty that can be satisfied by the available production levels in Peninsular Malaysia is up to 70% if expansion is allowed and 60% if the expansion is not allowed. The land available for expansion is 20% of the current plantation area in which the decision to delay expansion is made in certain regions.
- Palm-based biomass contributes to satisfying the demand of energy products such as syngas, biogas, electricity and transportation fuels through investment in conversion technologies in each region in which the production levels are proportional to the local demand.
- An increase of 50-55% of the current yield should be made to meet future demands outside Malaysia if expansion of current plantation will be stopped. This is attainable by best practices (i.e. nutrient and water management, pest control, etc.) since the potential yield can be up to 8 ton of CPO/ha/y.

These insights are helpful in developing a sustainable palm oil industry in which further land conversion will be stopped, thus risks in biodiversity losses and climate change impact are prevented. Although the case benefits the Malaysian economy in terms of potential revenue generation, this allows one to to identify whether palm oil can still be sustainable in the future on a business-as-usual case. Policy suggestions such as encouragement of best practices in oil palm plantation and palm oil milling can be drawn from this case study. The next case features the entire decision framework involving both economic and environmental impacts based on the expert value judgments given by several experts in Malaysia. The case not only maximises economic benefits but also minimises climate change impact, water impact and risks of biodiversity losses.

5.2. Case 2: Expert-Based Optimal Oil Palm Value Chain

For this case, the economic and environmental impacts are weighted based on ten experts that were asked to complete a short survey. This survey was based on the decision structure described in Section 4.1. A sample survey answer is converted into a pairwise comparison matrix and shown in Table 6. Descriptive judgments from the survey are translated into triangular fuzzy numbers (TFNs). For instance, if biodiversity losses

Table 6: Sample expert value judgment expressed as TFN's. The impacts, namely economic benefits (Eco), climate change impact (Cmc), water impact (Wat) and risks in biodiversity losses (Bio), are assessed based on four criteria

(a) Short-term benefits

	Eco	Cmc	Wat	Bio
Eco	<1,1,1>	<0.13,0.2, 0.33>	<0.13,0.2, 0.33>	<0.11,0.13, 0.17>
Cmc	<3,5,7.9>	<1,1,1>	<1,1,1>	<0.31,0.5, 0.83>
Wat	<3,5,7.9>	<1,1,1>	<1,1,1>	<0.31,0.5, 0.83>
Bio	<6,8,9.5>	<1.2,2,3.2>	<1.2,2,3.2>	<1,1,1>

(b) Long-term benefits

	Eco	Cmc	Wat	Bio
Eco	<1,1,1>	<0.11,0.13, 0.17>	<0.11,0.13, 0.17>	<0.11,0.13, 0.17>
Cmc	<6,8,9.5>	<1,1,1>	<1,1,1>	<1,1,1>
Wat	<6,8,9.5>	<1,1,1>	<1,1,1>	<1,1,1>
Bio	<6,8,9.5>	<1,1,1>	<1,1,1>	<1,1,1>

(c) Policy development

	Eco	Cmc	Wat	Bio
Eco	<1,1,1>	<1.2,2, 3.2>	<1.2,2, 3.2>	<0.11,0.13, 0.17>
Cmc	<0.31,0.5 0.83>	<1,1,1>	<1,1,1>	<0.18,0.33, 0.67>
Wat	<0.31,0.5 0.83>	<1,1,1>	<1,1,1>	<0.18,0.33, 0.67>
Bio	<6,8,9.5>	<1.5,3,5.6>	<1.5,3,5.6>	<1,1,1>

(d) Social acceptance

	Eco	Cmc	Wat	Bio
Eco	<1,1,1>	<1.2,2, 3.2>	<1.2,2, 3.2>	<0.11,0.13, 0.17>
Cmc	<0.31,0.5 0.83>	<1,1,1>	<1,1,1>	<0.18,0.33, 0.67>
Wat	<0.31,0.5 0.83>	<1,1,1>	<1,1,1>	<0.18,0.33, 0.67>
Bio	<6,8,9.5>	<1.5,3,5.6>	<1.5,3,5.6>	<1,1,1>

is very strongly more important than economic impact in terms of short- and long-term benefits, then the corresponding TFN for economic benefit over risk of biodiversity losses is $< 0.11, 0.13, 0.17 >$ while the TFN for risk of biodiversity losses over economic benefits is $< 3, 5, 7.9 >$. For each pairwise comparison matrix, the upper triangular matrix was obtained from the survey answers while the lower triangular matrix was calculated from the reciprocal of the upper triangular matrix. For this case study, ten experts with sufficient background in palm oil industry are asked to answer a questionnaire based on the decision structure in Figure (4). Based from the evaluation of the ten experts summarised in Table 7, the priority given to climate change impact and risks in biodiversity losses is higher compared to economic benefits and water impact. This would mean that the optimisation model will give more priority to the design of the value chain with lower risks in biodiversity losses and climate change impact. Individual assessments given by the experts also shows that out of the ten experts risks in biodiversity losses has the highest weight from six experts and climate change impact has the highest from four experts while economic benefits has the lowest weight from six experts. The highest priority given by one expert is 0.767 for risks in biodiversity losses while the lowest priority is 0.025 given to economic benefits.

Table 7: Final weights of the impacts based on different experts' set of survey answers

Objectives	**Experts**										**Geometric**	**Final**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**	**Weight**
Economic Benefits	0.221	0.245	0.185	0.075	0.127	0.050	0.025	0.128	0.189	0.069	0.107	0.119
Climate Change Impact	0.239	0.292	0.415	0.189	0.424	0.153	0.194	0.328	0.410	0.198	0.267	0.298
Water Impact	0.172	0.247	0.177	0.179	0.049	0.030	0.189	0.155	0.203	0.198	0.137	0.153
Risks of Biodiversity Losses	0.368	0.216	0.223	0.557	0.400	0.767	0.593	0.389	0.198	0.535	0.386	0.430

In order to determine the effects of changing the weights of the economic impact vs environmental impacts, sensitivity analyses were done. Figure 17 shows the resulting Pareto curves done by changing the weights of the impacts and obtaining an optimal solution. The curves shows trade-offs between profit and climate change impacts (17a), profit and water impact (17b) and profit and risks of biodiversity losses (17c). The climate change and water impacts are calculated from the operation of the technologies and are expressed proportional to the level of production. On the other hand, biodiversity losses are calculated proportional to the species richness obtained from [58, 59] and divided by the raster size in order to determine the richness per area. The objective of minimising the risks of biodiversity losses is expressed as the total of the species richness multiplied by the area invested for further expansion. A more sensible indicator for this is to normalise it based on the maximum total species richness obtained, giving a range of value from 0 (low risk) to 1 (high risk). From the results, it implies that the climate change impact can be reduced significantly by 11% in the profit range of 462 to 473 billion MYR, after which the required cut of the economic benefits is linearly proportional to the cut required for the climate change impact. Overall, 37% of the total climate change impact is reduced from modifying the value chain and reducing the profit by 32%. For water impact, the reduction in water consumption is proportional to the decline in economic value and it requires a reduction of 27% of the total profit to gain an 18% reduction in water consumption. However, a reduction of only 17% of the total profit is required in order to minimise risks of biodiversity losses to an insignificant level. These Pareto curves generated from sensitivity analysis can give insights into different scenarios in policy development of future oil palm value chains.

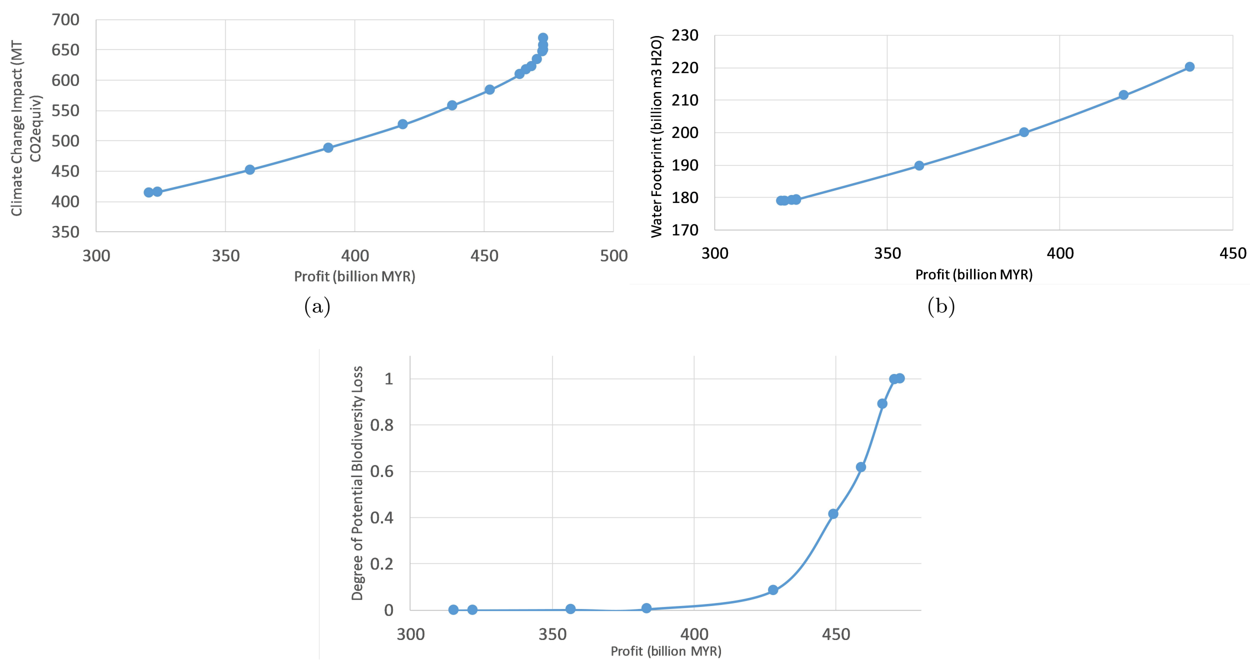


Figure 17: Sensitivity analyses performed for each environmental impact: (a) profit vs climate Change impact, (b) Profit vs water Impact and (c) Profit vs relative biodiversity losses

Using the set of weights generated from FAHP, the resulting satisfaction of export duties and domestic demand for the value chain is summarised in Figure 18. In this scenario, a user-defined minimum export duty is set to 60% of the required export duty, based on the scenario in the previous case in which further expansion will not be allowed. It implies that the model decides to minimise the export duties in order to minimise the environmental impacts arising from it. The domestic demand for crude palm oil is still satisfied. The export duties are initially 4.65 million tons per year and increase up to 7.59 million tons per year at the end of 2050. The result implies that the level of production of CPO is decreased in order to minimise the environmental impacts arising from it but still maintains domestic demand for CPO. Electricity is produced mainly in the region primarily because of the required electricity to run palm oil mills.

The levels of production of CPO for the expert-based solution are shown in Figure 19. Compared to the previous case, the levels of production decrease and the investment in small palm oil mills increases starting from the 2026. This results from the reduction of export duties to minimise environmental impacts such as climate change and water impacts. It is also observed that the shares of small palm mills in major producing regions, such as Johor and Perak, are higher than the large-scale mills. Even if the share of small palm oil mills increases throughout the planning period, the increase in production of CPO is still needed. For instance, the expert-based solution suggests an increase in production of CPO in Johor by 31% while increases of 160% and 100 % are observed in the Pahang and Perak regions respectively. If the export duties need to be cut at the beginning, incremental increases in production levels are required compared to the gradual increase observed in the first case. However, the level of production at the beginning of the planning horizon is also decreased dramatically.

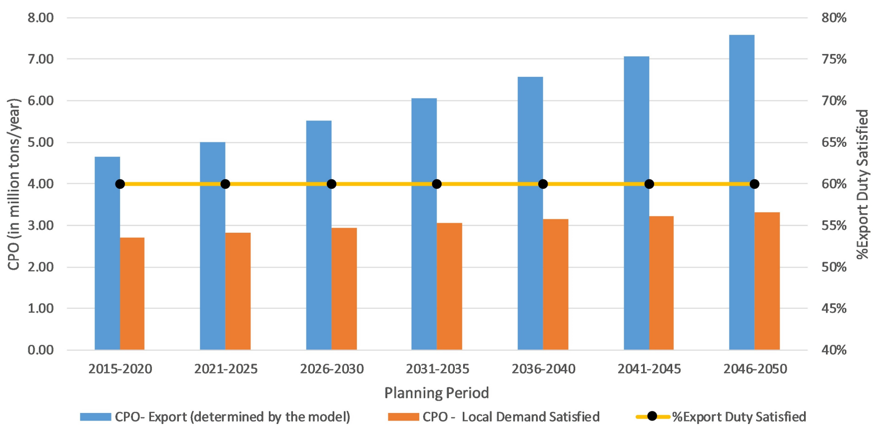


Figure 18: CPO demand and export satisfaction under expert-based optimal solution

The production of energy products and the investment of conversion technologies is illustrated in Figure 20. The same level of satisfaction of the required energy demand is observed in this case in relation to the first case. However, the demands for transportation fuels are satisfied by investment of upgrading units and use bio-oil product derived from pyrolysis. Similar to the first case, the investment and production levels of conversion technology in each region is based on the level of demands rather than the level of production of palm-based biomass. Transportation infrastructures play a major role in transferring biomass materials and energy products into different regions. The levels of energy products generation does not increase much except for the Pahang region, which shows a significant increase in production from 2040 to 2050. A major portion of energy products generated is electricity and majority of it is produced in Pahang. The expert-optimal solution implies the same investment and production levels of high-value products relative to that of the first case.

A summary of the different solutions at different objectives is shown in Table 8. The expert-based solution is

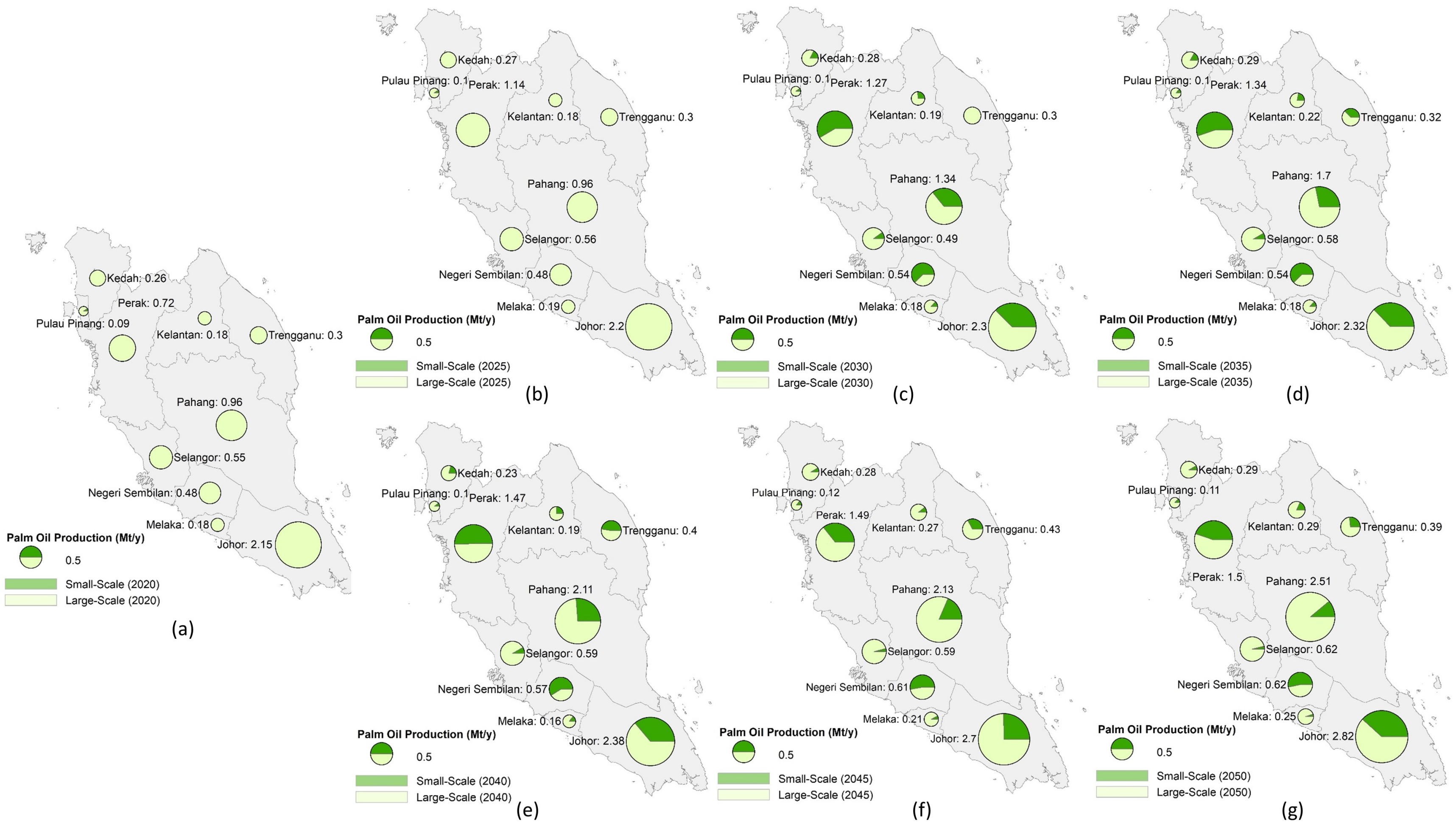


Figure 19: Palm oil production in Peninsular Malaysia for expert-based optimal solution in different planning periods: (a) 2015-2020 (b) 2021-2025 (c) 2026-2030 (d) 2031-2035 (e) 2036-2040 (f) 2041-2045 (g) 2046-2050.

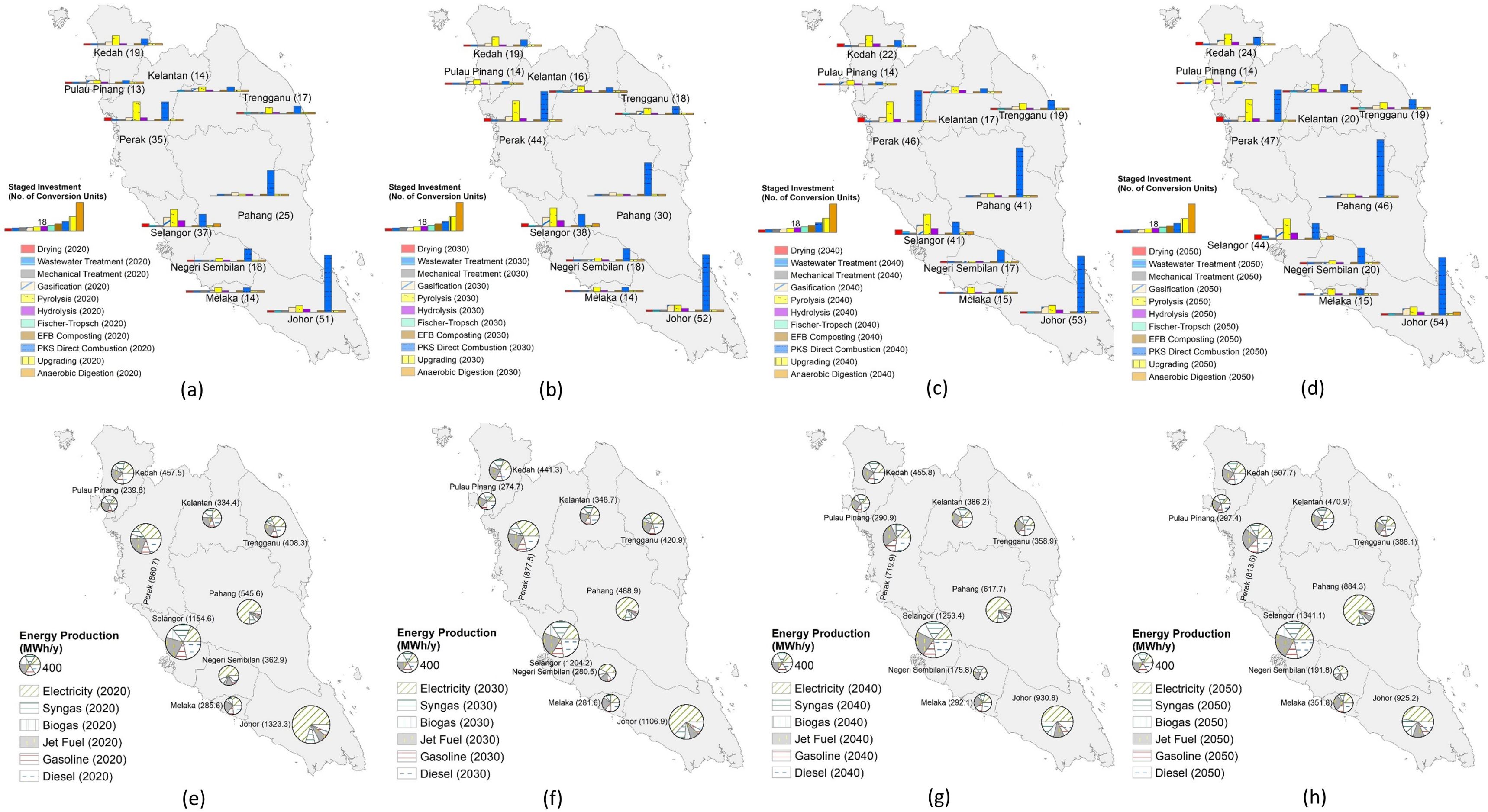


Figure 20: Staged Investment for (a) 2015-2020 (b) 2021-2030 (c) 2031-2040 and (d) 2041-2050 in number of conversion units and annual energy products generation for (e) 2015-2020 (f) 2021-2030 (g) 2031-2040 and (h) 2041-2050 in '000 MWh/y for the expert based optimal solution.

near to the optimal solution for minimum environmental impacts while needing a cut of 32% of the maximum profit. From this case study, the following insights can be drawn:

- Expert-based value judgment can integrate both economic and environmental objectives, giving priority to the objectives with higher weights. From the ten experts that were asked to fill the survey questionnaire for the AHP, the final set of weights aggregated by geometric mean show priority to risks in biodiversity losses, greater than the other three objectives. Of all the objectives, economic benefits are least prioritised.
- The optimal solution from these set of weights results in a cut of export duties up to the user-defined value. However, the production levels increases through time to continue satisfying the increasing global demand of crude palm oil.
- Sensitivity analysis shows how much profit can be sacrificed to gain environmental impact reduction. However, in the case of biodiversity losses, the economic benefits can still be maximised if the expansion of oil palm plantations is stopped.

Table 8: Summary of different optimal solutions under different objectives and the expert-based solution obtained based on the weights derived from FAHP.

	Profit (billion MYR)	Climate Change Impact (MT CO_2 equiv)	Water Impact (billion m^3 H_2O)	Relative Risks of Biodiversity Losses
Maximum Economic Benefits	473.0	668.8	239.9	1.000
Minimum Climate Change Impact	399.1	414.5	179.0	0.955
Minimum Water Impact	298.7	559.7	159.0	0.493
Minimum Risks of Biodiversity Losses	431.7	596.8	218.7	0.000
Expert-based Solution	**322.1**	**416.7**	**179.2**	**0.000**

The expert-based solution provides a balance between economic and environmental impacts based from the qualitative expert value judgment given. The case study demonstrates the capability of the decision framework to incorporate decisions such as production levels and investments as well as to gain insights on demand satisfaction, export duties, economic benefits and environmental impact reductions.

6. Conclusions

An integrated model was developed for optimal expert-based planning of oil palm value chains (OPVCs) considering resource production and transportation to satisfy product demand and export requirements subject to multiple objectives weighted based on experts' qualitative judgment. This comprises two major components: a mixed integer linear program (MILP) to generate optimal solution for the value chain and suggest important decisions such as technology investments, production level, plantation expansion, among others, and a fuzzy analytic hierarchy process (FAHP) decision model to incorporate stakeholders' or experts' value judgment into the design of value chain. The integrated model was able to considered expert value judgment in planning OPVCs which influences the priority between impacts generated by the value chain. The model was demonstrated using two cases: one that maximises economic benefits from the value chain, with and without plantation expansions, and the second is an expert-based case study considering both economic and environmental impacts of the value chain. For the first case, a sensitivity analysis was also performed to gain insights into the encouraging best practices to improve palm oil yield and prevent further expansion of the current plantation. For the second case, Pareto curves were generated to determine the trade-offs between economic benefits and environmental impacts. These analyses allow the decision-maker to gain insights when developing policies for a sustainable palm oil industry. Such insights that can be used for policy-making includes incentives for technological investments, policies related to new palm oil mills, policies related to expansion of new plantations, among others

The first case, which is a business-as-usual case, determines the maximum economic benefits subject to the policy of no further plantation expansion being allowed. Even if expansion by an area of up to 20% of the current plantation is allowed, it is not sufficient to satisfy both the demands for palm oil in Peninsular Malaysia and the exports required internationally. However, with best practices, which require that the yield be increased by 50-55%, this requirement can be attained throughout the planning horizon. It can also be inferred from the case study that there might be enough time to develop methods to improve the yield of palm oil, since the optimal results allows the value chain to fulfill its required production up to 2025 and only a small decrease is required at the end of 2030. The decision framework also demonstrates the conversion of palm-based biomass to energy products, providing an additional revenue of 15%. However, the investment into new conversion technologies for the value chain needs to be subsidised from the revenue generated by the palm oil mills. The integrated model allows circular pathways to be considered, one of which is demonstrated is that of electricity required by palm oil mills being supplied by cogeneration using palm kernel shells.

The second case shows the expert-based optimal solution from the weights obtained using FAHP. Based from the experts asked to fill the survey questionnaire, the priority weights show that the impact with the highest priority is the risks to biodiversity losses while the least priority is given to the economic benefits. The resulting optimal solution shows a reduction of exports to a minimum. Compared to the first case, the profit is reduced by 32% in order to obtain the minimum climate change and water impacts. It also suggests investment in conversion technologies to convert palm-based products into: electricity to satisfy a portion of the electricity demand and to use in technologies in the value chain; and into high-value energy products such as transportation fuels. Sensitivity analyses were performed to determine the changes in economic benefits with respect to each of the environmental impacts. Relative risks in biodiversity losses are minimised with the least reduction in profit and are reduced by not allowing further expansion of oil palm plantations. Overall, the second case demonstrates the whole decision framework for OPVCs.

The results of the case studies provide insights for future policy-making and for large-scale deployment of technologies to convert palm-based biomass such as empty fruit bunches (EFB), palm kernel shells (PKS) and palm oil mill effluent (POME). Future work includes considering other biomass materials such as palm mesocarp fibre (PMF) and oil palm fronds (OPF), and the application of the decision model to other value chain systems. The tool can also be extended to account for uncertainties resulting to financial risks. Strategies for stakeholder engagements will also be considered. These involve discussions on other possible factors to be included in the value chain framework, updating the current data, presenting and validating the results with the stakeholders. Expert engagement will be conducted to know their views about the preliminary results. Workshops will be done also to demonstrate and disseminate the tool and engagement through social media will be conducted to obtain public perception. These allow to account for a more detailed modelling of the oil palm industry in Malaysia, utilising databases other than literature data such as local databases, pilot plant data, among others.

7. Acknowledgment

The authors would like to thank the Newton Fund and the Engineering and Physical Sciences Research Council for financial support of this work through the BEFEW project (Grant No. EP/P018165/1) and the Science & Technology Facilities Council (STFC) ODA Institutional Award.

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